TRANSACTIONS OF

THE ROYAL SOCIETY OF CANADA

SECTION IV
GEOLOGICAL SCIENCES
INCLUDING MINERALOGY

THIRD SERIES—VOLUME XLVIII—SECTION IV
JUNE, 1954

OTTAWA
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CONTENTS

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SECTION FOUR

PRESIDENTIAL ADDRESS

Shale: A Study in Nomenclature

By T. H. CLARK

THE subject of this paper may not appear to have much appeal to current geological workers or to be of much importance to them. That it lacks appeal is fully admitted; that it is not important must be strongly denied. The word "nomenclature," defined in most dictionaries as a "system of names," is derived directly from the Latin, and there has never been any doubt as to its meaning. "Shale" has had a long history of geological use, but even now there is divergence of opinion as to its definition, and few geologists agree as to the precise naming of all of its varieties, save perhaps the disciples of some of the modern schools of thought that have devoted much time to its study. Shale, as I define the word for use, is a detrital sedimentary rock, the bulk of whose particles have a diameter less than 1/16 mm.

Only three of the main types of sedimentary rocks are important enough to occur in amounts greater than 1 per cent, namely, shale, sandstone, limestone. Authorities agree that half or more of all sedimentary rocks fall into the wide category of shales. Why is it, then, that sandstones and limestones, each of which make up but a fraction of the volume of shales, have nomenclatures which include several times as many names as are found in the nomenclature of shale? If we discount for the moment the many varieties of all types to be found in Grabau's classification (1920), and omit the pyroclastic rocks, then, save for adjectival qualifications, shale possesses as classificatory unit names only siltstone and siltrock, mudstone and mudrock, claystone and clayrock, and argillite. Sandstones have been described as arkose, quartzite, flagstone, freestone, graywacke, orthoquartzite, gannister, subgraywacke, grit, etc., and limestones have been called coquina, coquinoid, lithographic stone, oölite, marl, tufa, chalk, travertine, klintite, spergenite, not to mention the many varieties of dolomite. There are several reasons for this disparity, one being that the fineness of grain of shales has hindered our understanding of its mineral content, and another, the notion, formerly usually accepted, that shales are comparatively useless. Neither of these reasons obtains today, and the upsurge of investigation into the properties of shale has contributed a vast amount of knowledge that has not yet been systematized into a uniformly accepted nomenclature.

It should be stated here that there is nothing original in this paper other

than a point of view. The author has drawn freely on the writings of the last decade, and modern tendencies especially hold his interest. Although the literature has not been covered completely, no significant development has gone unnoticed.

First of all, before considering shale, it seems best to ponder the significance and use of nomenclatures. They depend upon classifications. Substances like rocks or minerals may be classified merely for the sake of a classification. Thus shales might be divided into black, gray, white, red, green, etc., varieties. This division would be perfectly scientific, for after all, scientific endeavours consist basically in the application of some sort of a "yardstick," be it feet and inches, volume, chemical composition, reaction to X-rays, or molecular pattern, in such a way as to produce results which can be reproduced by other scientists, and which are, in a sense, predictions. Minerals were once classified primarily according to colour, but the application of the colour yardstick was attended by so many difficulties that it has been relegated to a minor role in mineralogical classification.

Hence, yardsticks should produce a classification that can be both readily arrived at and profitably used. As a further example, the classification of the Foraminifera remained an academic exercise yielding a perfectly satisfactory result which, except for indicating the gross taxonomy of the group, was of no further use. The intense interest taken by petroleum geologists in these fossils since about 1920 has led to refinements of the previous methods. The classification has now become a reliable and invaluable tool in elaborating the differentiation of and the evolutionary trends among the Foraminifera, and it has contributed immeasurably to the production of petroleum itself.

So, in the case of shale, a classification that can be put to good use depends upon the application of a variety of well-chosen criteria, and with such a classification the nomenclature should follow naturally. Although the criteria applied to date are numerous, the list seems likely to continue to grow. Some of the most used and useful that come to mind are: hardness; colour; texture (grain size and shape and cementing materials); structure (degree of sorting, lamination, porosity and permeability, compaction and fissility); and composition (original, introduced or rearranged minerals and the chemical nature thereof). Almost any of the above criteria will yield a fractionally satisfactory classification, and conjunction with others will increase the value and effectiveness of the result.

Secondly, some thought should be given to the aims, function, and uses of a classification. What do we expect to get out of a classification? Separation using the criteria of colour, hardness, cement, etc., would yield truly scientific groupings, yet they would be of limited academic or practical value. We should be able to read from the analysis of a shale something about such features as: parent rock (provenance); residual or transported origin; environment of deposition in respect to erosion of surrounding lands, transportation of debris, and depth and type of water receiving

deposit; post-depositional changes or diagenesis by reaction with groundwater, reaction between constituent grains, or chemical and physical metamorphism.

It is in order here to digress from the two lists of features already given. Those in the first list are purely descriptive, whereas those in the second are genetic. In spite of repetition it should be emphasized again that many classifications, good in themselves, have failed because they do not adequately separate these two sets of criteria. Those interested only in the origin of a shale would draw conclusions from a purely descriptive treatment that might not be in accord with the descriptive classification in question. And, *vice versa*, a worker interested only in the kind of shale would find difficulty in extracting satisfactory information from a purely genetic classification. Classifications should be primarily descriptive. Any incorporation of genetic data should be of secondary importance (see Ireland, 1947, p. 1481; Krumbein, 1947, p. 168; Krynine, 1948; Pettijohn, 1949, p. 179; Russell, 1949).

Thirdly, the type of classification and the requisite criteria should be considered. Before establishing a routine using the yardsticks listed above to determine which of the several environmental conditions governed the origin of the sediment, we must recognize the limitations imposed by the situation of the worker. We should know beforehand whether to develop a classification that will be of use, say, (*a*) in the field; (*b*) at a desk, with binoculars and simple chemical aids; (*c*) for petrographic study of thin sections; (*d*) in a complete chemical analysis, or (*e*) with X-ray apparatus. Obviously, techniques involved for (*d*) and (*e*) would be useless to a man on a mountainside in northern Alberta. The great majority of investigators work under conditions (*a*) and (*b*), and would prefer to use a classification in accord with their experience (see Shrock, 1948), though their results might contribute to an elaboration of the classification itself. Actually such a classification would be a thoroughly satisfactory basis for further work under conditions (*c*), (*d*), and (*e*).

Now as to nomenclature. With rare exceptions, e.g. Grabau (1920), all classifications of shale begin with a consideration of grain size. There is a fairly general agreement that 1/16 mm. should be the accepted limit separating sand-size particles from those of smaller dimensions, i.e. shale-size particles. There is less agreement that there should be a second limit at 1/256 mm. separating larger particles classed as silt from smaller ones called clay particles. Siltstone and claystone are the corresponding consolidated products. In such a scheme there is no size definition for mud or mudstone.

Simple though such a separation of shale into siltstone and claystone may appear to be, there has been and still is wide divergence in the use of these two terms. Dapples, Krumbein and Sloss (1950, p. 14) prefer to use 1/100 mm. as the particle size limit separating siltstone from claystone "for experience has shown that siltstones whose most abundant particles exceed

this diameter show the field characteristics of sandstones: whereas finer sediments have the characteristics of typical shales." The coarse-grained shales, as they might be called, are included by those authors both with sandstones (*ibid.*, Table 2) and with shales (*ibid.*, Table 3). Theirs is merely a variation of the grain-size criterion, though in the writer's opinion an unfortunate one, for the sandstone table contains many shale rocks, and as a consequence, certain shale rocks do not occur in the table of shales.

Siltstone and claystone are used with reasonable uniformity save for the proviso by most modern authors that lamination should be absent. "All claystones or siltstones which show bedding in thin units are called shales" (Dapples *et al.*, 1950, Table 3). Also, there is still some difference about the meaning of mudstone. Thus Shrock (1948, p. 124) calls mudstone a "partly indurated argillaceous rock which slakes readily to mud when repeatedly dried and wetted." Trask (1950, p. 33) calls it a deposit of clay particles. Shand (1947, p. 177) refers to it as a consolidated clay, without laminations. Because we have available the terms siltstone, and claystone, ideally not overlapping, but in practice always doing so, why not use the terms "mud" and "mudstone" and restrict them to deposits partly silty, partly clayey (Thompson, 1947, p. 338). Thus the first step in a preferred classification and nomenclature would be to divide shale into siltstone, mudstone, and claystone.

Though the limitation of the term shale to fine-grained detrital sedimentary rocks and its further subdivision, again determined by grain size, into siltstone, mudstone, and claystone, has extreme simplicity and reasonable ease of application in its favour, no general agreement on it can be found in the literature. Pirsson and Knopf (1947, p. 252), and Shrock (1948, p. 123) use shale in the above preferred sense. Almost all other modern writers insist upon lamination as a primary requisite for a shale. Those rocks lacking lamination are called siltstones, mudstones, or claystones by Pettijohn (1949, pp. 269–70), Twenhofel (1950, p. 322), and Ingram (1953, p. 870); siltstones by Trask (1950, p. 33); mudstones by Holmes (1945, p. 54), Shand (1947, p. 177), Gilluly, Waters and Woodford (1951, p. 602), and Picard (1953, p. 1076); and claystones by Flawn (1953, p. 563). Garrels (1951, p. 208) and Lahee (1952, p. 805) limit shale to a minor role among these fine-grained rocks.

Flawn (1953, p. 562) considers shale to be properly a structural term. Etymologically, he is correct, but usage has long since discounted the necessity for a shell-like (i.e., conchoidal) fracture as a charactertistic. The decision to drop terms such as shale (which Flawn did not advocate) because of a misapprehension when the name was first applied (e.g., pyroxene) would create enduring sources of confusion, and probably this would never be accepted.

As for lamination, that is a structural characteristic, which should be described, when necessary, by a modifying adjective, as should also fissility (sometimes independent of lamination) or massiveness (flaky, flaggy, mas-

sive, *vide* Ingram, 1953) as in massive siltstone, fissile claystone, etc. Ingram has suggested the following classification and nomenclature of rocks composed of silt, mud, and clay.

No connotation as to breaking characteristics	Massive	Fissile
Siltrock	Siltstone	Silt shale
Mudrock	Mudstone	Mud shale
Clayrock	Claystone	Clay shale

Though there is merit in the suggestion, it is unsatisfactory because it assumes that a shale must be fissile.

Description by means of an adjective should also apply in the case of colour (e.g., red fissile claystone); of important and obvious minerals (e.g., black, massive, micaceous, mudstone); and possibly one or two other characteristics such as cement and cementation, hardness, and porosity, though reference to these last few should be included in the description of the rock, rather than its name. The writer agrees with those who object that "gray, quartzose, laminated mudstone" is a clumsy name for a rock type, but clumsiness is preferable to chaos. Doubtless the four basic terms so far discussed—shale, siltstone, mudstone, and claystone—will eventually receive as nearly universal acceptance as have conglomerate, sandstone, and shale.

There remains one term not yet mentioned, namely, argillite. Here, too, confusion reigns. Dana (1895, p. 80) wrote: "ARGILLYTE, or clay-slate (Phyllite). A slaty rock, like shale, but differing in breaking into thin or even slates or slabs." Chamberlin and Salisbury (1904, p. 473) defined it as a "Clayey rock; usually applied to hard varieties only." "Argillite is a clay or shale hardened by crystallization" (Grout, 1932, p. 269). "Hard, indurated shales devoid of fissility are called argillites" (Pirsson and Knopf, 1947, p. 255). "Argillite, slate, phyllite, and schist are members of a series of metamorphosed argillaceous materials" (Shrock, 1948, p. 124). "An *argillite* is a rock derived from a siltstone or shale that has undergone a somewhat higher degree of induration than is present in those rocks" (Pettijohn, 1949, pp. 269, 280). "Argillite is a fine-grained argillaceous material that is massive and somewhat indurated and hard" (Grim, 1953, p. 2). "A claystone composed entirely of clay minerals. . . . Indurated argillaceous rock without visible parting, cleavage or foliation, in which less of the micaceous paste and clay minerals have been reconstituted to sericite, chlorite, etc. . . . Clayslate. Similar to argillite but with a parting" (Flawn, 1953, p. 563). "Argillite is a particularly hard shale, high in silica, and presumably held together by silica minerals that were formerly in a colloidal state" (Spock, 1953, p. 172).

Thus, in general, argillites have been defined as shaly rocks devoid of

lamination, and hence might properly be called unlaminated or massive siltstones, mudstones, or claystones. They are hard, possibly because of strong cementation by crystalline or colloidal silica, or incipient metamorphism; in the latter case, as suggested by Shrock (1948, p. 124), the rocks have reached, if not passed, the threshold of metamorphism. Because of disagreement, and because secondary processes are involved by implication, the writer favours dropping the word argillite from our nomenclature. As a substitute, there could be no objection to prefixing "strongly indurated" to the terms shale, siltstone, mudstone, or claystone, adding laminated or unlaminated when appropriate. If it is eventually found that the name argillite is needed it should be re-defined. This development has occurred with the term greywacke. Long misunderstood and misapplied (Twenhofel, 1950, p. 317), it has recently been re-defined and is now a widely accepted term applied to a sediment of the sandstone group.

Such a simplified scheme as is here proposed would allow us to take stock, to assess the importance or abundance of certain rock types, and then, if desirable, to give names to the important varieties. The author's chief plea is for simplification of the nomenclature of shales. Whether or not this may ultimately be achieved by a refinement of a binomial (e.g., micaceous shale, fissile claystone, or arkosic siltstone; see Krynine, 1948), or trinomial, or even quadrinomial (hard, fissile, micaceous mudstone) system, or by the translation of such names into Greek (e.g., hydroargillutyte of Grabau, 1920), or by the application of geographic names (e.g., spergenite among the limestones), or by the coining of new names (e.g., arkose among the sandstones), remains a question to be answered by the good sense of those geologists who will be better provided with requisite information than we are today.

Many topics are being investigated that must eventually influence our terminology. Three only will be mentioned here. First, there is clay mineral differentiation by various new methods, such as X-ray techniques (Grim, 1953); this is a geological study, initiated by geologists for geological ends, though the results will certainly be of much value in other disciplines. Second, foundation problems in engineering (Philbrick, 1950), though initiated by engineers, are being investigated jointly with geologists, and the results may well modify our concepts of the properties of shale. And third, pedology, which might well have been a subdivision of our science, is fast becoming a full-fledged science in its own right. Through our studies of clay minerals we shall be in a position to make important contributions to pedology, and in return may profit greatly from the biochemical research carried out in pedological laboratories upon such topics as the roles of bases in clay minerals and the action of organic and inorganic colloids in soils.

Nothing has been said regarding the use of shale in the ceramic industry, of its importance in forming petroleum traps, or of the deposits of copper or uranium it may contain. The first two are being actively investigated,

and the abundance of work being done may influence the development of shale nomenclature.

REFERENCES

CHAMBERLIN, T. C. and SALISBURY, R. D. (1904). Geology, vol. I. New York.

DANA, J. D. (1895). Manual of geology. 4th ed., New York.

DAPPLES, E. C., KRUMBEIN, W. C., and SLOSS, L. L. (1950). The organization of sedimentary rocks; Jour. Sed. Petrology, vol. 20, no. 1, pp. 3–20.

FLAWN, P. T. (1953). Petrographic classification of argillaceous . . . rocks . . .; Bull. Am. Assoc. Pet. Geol., vol. 37, no. 3, pp. 560–5.

GARRELS, R. M. (1951). A textbook of geology. New York.

GILLULY, J., WATERS, A. C., and WOODFORD, A. O. (1951). Principles of geology. San Francisco.

GRABAU, A. W. (1920). Textbook of geology, vol. I. Boston.

GRIM, R. E. (1953). Clay mineralogy. New York.

GROUT, F. F. (1932). Petrography and petrology. New York.

HOLMES, A. (1945). Principles of physical geology. New York.

INGRAM, R. L. (1953). Fissility in mudrocks; Bull. Geol. Soc. Amer., vol. 64, pp. 869–78.

IRELAND, H. A. (1947). Terminology for insoluble residues; Bull. Am. Assoc. Pet. Geol., vol. 31, no. 8, pp. 1479–90.

KRUMBEIN, W. C. (1947). Analysis of sedimentation and diagenesis; Bull. Am. Assoc. Pet. Geol., vol. 31, no. 1, pp. 168–74.

KRYNINE, P. D. (1948). The megascopic study and field classification of sedimentary rocks; Jour. Geol., vol. 56, pp. 130–65.

LAHEE, F. H. (1952). Field geology. 5th ed., New York.

PETTIJOHN, F. J. (1949). Sedimentary rocks. New York.

PHILBRICK, S. S. (1950). Foundation problems in sedimentary rocks; in Applied sedimentation. New York.

PICARD, M. D. (1953). Marlstone—a misnomer as used in Uinta Basin, Utah; Bull. Am. Assoc. Pet. Geol., vol. 37, no. 5, pp. 1075–7.

PIRSSON, L. V. and KNOPF, A. (1947). Rocks and rock minerals. 3rd ed., New York.

RUSSELL, R. D. (1949). Trends in sedimentology; Bull. Am. Assoc. Pet. Geol., vol. 33, no. 7, pp. 1145–53.

SHAND, S. J. (1947). The study of rocks. London.

SHROCK, R. R. (1948). A classification of sedimentary rocks; Jour. Geol., vol. 56, pp. 118–29.

SPOCK, L. E. (1953). Guide to the study of rocks. New York.

THOMPSON, H. D. (1947). Fundamentals of earth science. New York.

TRASK, P. D. (1950). Dynamics of sedimentation; in Applied sedimentation. New York.

TWENHOFEL, W. H. (1950). Principles of sedimentation. 2nd ed., New York.

TRANSACTIONS OF THE ROYAL SOCIETY OF CANADA
VOLUME XLVIII : SERIES III : JUNE, 1954
SECTION FOUR

Isotopic Analyses of Anomalous Lead Ores

By R. M. FARQUHAR and G. L. CUMMING

Presented by J. T. WILSON, F.R.S.C.

A NUMBER of recent investigations have shown that variations exist in the isotopic constitutions of many naturally occurring elements. These variations are of interest to geology because they reflect the geological history of the rocks or minerals of which the particular elements are constituents, and may give quantitative information about processes and conditions in different geological environments.

Studies of the isotopes of common or ore leads have proved particularly interesting since the isotopic composition of many leads depends on their ages of deposition. Common lead consists of the four isotopes Pb^{204}, Pb^{206}, Pb^{207}, and Pb^{208}, of which Pb^{206}, Pb^{207}, and Pb^{208} are identical with the isotopes produced by the decay of U^{238}, U^{235}, and Th^{232} respectively. The isotopic analyses of lead ores published by Nier (1938, 1941) and subsequent investigators (Collins, Russell, and Farquhar, 1952; Vinogradov, Zadorozhnyi, and Zykov, 1952; Kulp, Owen, Eckelman, and Bate, 1953; Allan, Farquhar, and Russell, 1953; Geiss, 1954; Russell, Farquhar, Cumming, and Wilson, 1954) indicate that in younger ores the amounts of the isotopes Pb^{206}, Pb^{207}, and Pb^{208} are more abundant relative to Pb^{204}. The differences in isotopic composition of ores of different age may be interpreted by assuming that the uranium and thorium distributed throughout the source rocks from which lead ores have been concentrated have been decaying to Pb^{206}, Pb^{207}, and Pb^{208} thus continuously altering the isotopic composition of the lead in the source. Lead ores concentrated from these source rocks early in geological time will contain smaller amounts of Pb^{206}, Pb^{207}, and Pb^{208} than ores of recent geological age, because the isotopic composition of the lead ores will remain unchanged after the process of concentration has separated them from uranium and thorium.

When the experimental data are arranged in order it is found that the majority of lead ores have isotopic ratios which follow a regular pattern. A simple theory, based on the work of Alpher and Herman (1951), has been developed to explain this pattern. It is assumed that uranium, thorium, and lead were distributed uniformly throughout the source rocks from which most of the lead ores in the world were concentrated. This is the only explanation of the pattern yet advanced, and suggests that the ores have come from an extremely homogeneous source. It implies that most ores have not spent much time in the earth's crust (which is cer-

tainly not uniform in composition), but have come fairly directly from the upper part of the mantle (which may well be uniform in composition). On the basis of this theory, curves have been constructed showing the change in the abundance ratios Pb^{206}/Pb^{204}, Pb^{207}/Pb^{204}, and Pb^{208}/Pb^{204} with the time of deposition of the ore (Russell, Farquhar, Cumming, and Wilson, 1954).

It has also been found that a relatively few leads have much greater Pb^{206}/Pb^{204} and Pb^{208}/Pb^{204} ratios than do the "ordinary" types which fit closely the abundance-time curves. Such leads have been termed "anomalous." The high Pb^{206}/Pb^{204} and Pb^{208}/Pb^{204} values suggest that the anomalous leads have been associated with much higher concentrations of uranium and thorium than are found in the usual source rocks of lead ores and have apparently experienced more complex geological histories. This paper deals mainly with this anomalous class of lead ores, and includes further isotopic data recently obtained for lead samples from deposits in North America. These results were all obtained using the mass spectrometer and lead isotope analysis technique described previously (Collins and Freeman, 1951; Collins, Russell, and Farquhar, 1953).

The Sudbury Galenas

The results of isotopic analyses of fourteen galena samples from the Sudbury, Ontario, area have already been reported (Russell, Farquhar, Cumming and Wilson, 1954). Four of these leads were of the ordinary type and ten were of the anomalous type. One example of each of these classes is reproduced in Table I to indicate the extremes of variation in

TABLE I

Lead Isotope Abundances of Galenas from Sudbury and Noranda Areas

No.	Location	Lead isotope ratios		
		Pb^{206}/Pb^{204}	Pb^{207}/Pb^{204}	Pb^{208}/Pb^{204}
233	*Frood Mine, 400′ level Sudbury area (post-ore slip)	23.10	16.90	45.04
232	*Frood Mine, 3300′ level Sudbury area (Disseminated in wall-rock)	15.99	15.84	36.54
518	Treadwell-Yukon Mine (interior of Sudbury Basin)	16.15	15.60	35.94
368	Quemont Mine, Noranda, Que. 4th level	20.80	16.19	44.93
367	Quemont Mine, Noranda, Que. 12th level	21.26	16.17	43.68

Reproducibility of ratios quoted in Tables I, III and IV is ±0.8 per cent.
*From Russell, Farquhar, Cumming and Wilson, 1954.

isotopic composition which are encountered in this limited region. Also included in Table I is a recent analysis of a galena sample from the Treadwell-Yukon mine located in the interior of the Sudbury basin. The similarity of the isotopic constitution of this lead and the constitutions of the ordinary leads from the mines at the rim of the Sudbury basin (typified by no. 232, Table I) suggests that the Treadwell-Yukon deposit was introduced at approximately the same time as these other leads. An age for this period of 1200 ± 200 million years has already been determined from the abundance-time curves (Russell, Farquhar, Cumming and Wilson, 1954).

It has been pointed out that the high values for the Pb^{206}/Pb^{204} and Pb^{208}/Pb^{204} ratios found for ten of the fifteen samples from the Sudbury area suggest that these leads have been associated with rocks comparatively rich in uranium and thorium. Assuming that the anomalous isotopic composition of these ten leads is due to the mixing of a single ordinary lead with different proportions of a single radiogenic lead, the present-day average thorium to uranium ratio in the source of the radiogenic additions has been calculated to be 5.2 (Russell, Farquhar, Cumming and Wilson, 1954). This value is much higher than the average ratio of thorium to uranium of 3.5 calculated from radioactivity data (Senftle and Keevil, 1947) and the lead isotope abundance-time curves. Keevil (1944) has reported the uranium and thorium contents of several rock samples from the Sudbury area. His values, given in Table II, show a variation in the

TABLE II

Thorium and Uranium Contents of Rocks from the Sudbury Area
(from Keevil, 1944)

Rock type	Location	Th × 10^6 (gms/gm)	U × 10^6 (gms/gm)	Th/U
Granite	Creighton Mine, Ont.	17 ± 4	3.5 ± 0.7	4.8
Norite	Outcrop, Creighton, Ont.	4.3 ± 0.8	1.5 ± 0.4	2.9
Norite	40 level, Creighton Mine, Ont.	2.1 ± 0.4	0.71 ± 0.14	3.0
Olivine diabase	20 level, Creighton Mine, Ont.	2.4 ± 0.3	0.97 ± 0.2	2.4
Olivine diabase	Worthington, Ont.	15 ± 3	2.2 ± 0.3	6.8

thorium to uranium ratio of 2.4 to 6.8. However, the thorium and uranium contents of those rocks having high thorium to uranium ratios are several times greater than the radioactive contents of the rocks with lower thorium to uranium ratios. It is conceivable that some radiogenic lead was extracted from these more active rocks, mixed with ordinary lead, and subsequently deposited as anomalous galenas. The anomalous galenas were all found in minor quantities in post-ore slips, so that radiogenic lead need only be extracted on a very local scale to significantly alter the isotopic

composition of small quantities of ordinary lead. In addition, recent geochemical studies (Brown *et al.*, 1953) indicate that considerable proportions of the radioactive constituents of igneous rocks are held interstitially. The radiogenic lead produced by the decay of such interstitial uranium and thorium would be susceptible to removal by leaching, without necessitating the complete solution of the rock.

Regardless of their exact mode of formation, anomalous leads of variable isotopic composition appear to be characteristic of deposits where galena is of very minor extent compared with the main mineralization. Table I gives the results of analyses of two samples of the Quemont Mine, Noranda, Quebec, both of which are anomalous, and significantly different in isotopic composition. No quantitative conclusions regarding ages of deposition or thorium to uranium ratios can be drawn from these two results, but it seems probable in view of the rare occurrence of galena in the mine, that the anomalous nature of the leads is due to the same process which has given rise to the anomalous Sudbury leads.

Bunker Hill and Sullivan Mine Galenas

In an effort to determine the source and mechanism of radiogenic additions which give rise to anomalous leads, a suite of galenas from the silver-lead-zinc districts of Idaho was analysed. Although galena is one of the major ore minerals of the deposits in the Cœur d'Alene district, it has been found (Keevil, 1950) that the ores there are several times more radioactive than average sulphides. The amount of radiogenic lead produced by this active material since the deposition of the ores would be insufficient to change the isotopic composition of the ore lead. However, radiogenic additions might have occurred had the ore previously existed in some highly disseminated form in contact with an equally radioactive source.

The analyses given in Table III are identical within the experimental error, and indicate that isotopic variations on the scale observed in the Sudbury deposits do not exist. The lead isotope ratios fit the abundance-time curves, and suggest an age of 1030 ± 290 million years for the de-

TABLE III

Lead Isotope Abundances of Galenas from Bunker Hill and Sullivan Mine, Kellog, Idaho

No.	Depth with respect to sea level	Pb^{206}/Pb^{204}	Pb^{207}/Pb^{204}	Pb^{208}/Pb^{204}
577	+3150′	16.69	15.82	36.79
578	+1200′	16.55	15.72	36.60
579	+ 850′	16.56	15.73	36.68
580	− 150′	16.58	15.75	36.75
581	− 350′	16.54	15.72	36.62
Average		16.58	15.75	36.69

posits. This value agrees within the estimated limits of uncertainty with an age of 850 ± 50 million years determined from the radiogenic Pb^{207}/Pb^{206} ratio in a sample of uranium ore from the Sunshine Mine, Kellogg, Idaho (Kerr and Kulp, 1952), and is further evidence for a Precambrian age for the deposits in the Cœur d'Alene district.

The Tri-State Galenas

Among the twenty-five common lead samples analysed by A. O. Nier (1938; Nier *et al.*, 1941), two from Joplin, Missouri, had high Pb^{206}/Pb^{204} and Pb^{208}/Pb^{204} ratios. An investigation of a suite of galenas from the Tri-State district was undertaken to determine whether the ores

TABLE IV

Lead Isotope Abundances of Tri-State Mine Galenas

No.	Mine	Bed	Lead Isotope Ratios Pb^{206}/Pb^{204}	Pb^{207}/Pb^{204}	Pb^{208}/Pb^{204}
316	Diamond Joe	Chester Limestone	21.38	16.16	41.03
318	Weber-Westside	D–E	22.15	16.21	41.63
320	Howe (ave. of 2 analyses)	E	22.29	16.27	41.88
315	Federal-Jarrett	G–H	22.70	16.25	42.16
319	Kitty	G–H	22.73	16.31	42.07
314	Weber-Westside	G–H	22.12	16.22	41.63
317	Grace B	J	22.77	16.29	42.25
321	Otis White	K	22.77	16.28	42.13
323	Blue Goose No. 1	M	22.07	16.24	41.87
231	Westside	M	22.16	16.31	41.98
322	Blue Goose No. 2 (ave. of 2 analyses)	O	21.83	16.14	41.35

of this area were anomalous. Table IV gives the results of eleven isotopic analyses of galena samples supplied through the courtesy of J. P. Lyden of the Tri-State Mines. The values of the Pb^{206}/Pb^{204} and Pb^{208}/Pb^{204} ratios are higher than average, and vary by as much as 6 per cent and 2½ per cent respectively. These variations are much smaller than those observed for the Sudbury leads. Unfortunately the differences in the Pb^{207}/Pb^{204} ratios are of the same order of magnitude as the uncertainties in the results, and it is impossible to draw any quantitative conclusions regarding the time of the radiogenic additions by the methods described previously (Russell, Farquhar, Cumming and Wilson, 1954).

Contrary to the extremely sudden changes in isotopic constitution of the leads found in the Sudbury mines, the composition of the Tri-State district leads appears to vary slowly and systematically with depth. Figure 1 shows a plot of the variations in the isotopic constitution of the galenas against their positions in the stratigraphic column, which represents an

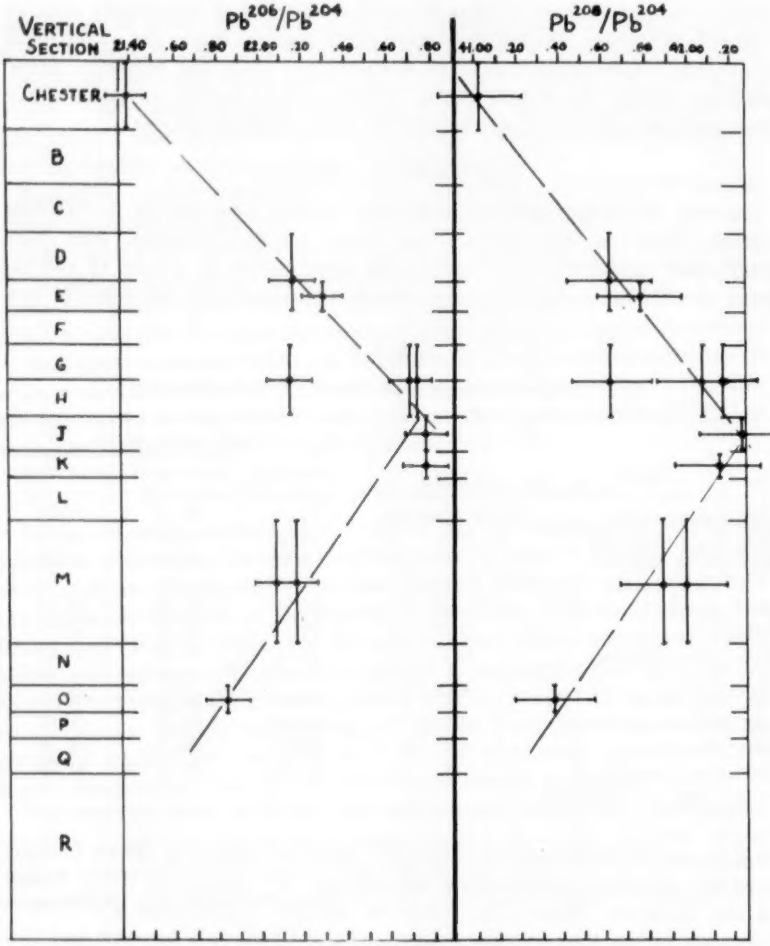


FIGURE 1—Variation of isotopic abundances with depth, Tri-State lead ores.

average vertical cross-section of the various sedimentary rock formations in the Tri-State area. This graph indicates that the radiogenic lead content of the galenas increases steadily with depth to a certain level in the column, and then appears to decrease with further increase in depth. The reason for this particular distribution is at present unknown. The most important point which can be made is that the deposition of these ores must have involved additions of considerable quantities of radiogenic lead, possibly leached from older rock formations which were relatively rich in uranium and thorium. Many more samples from this region must be analysed with

an accuracy greater than that at present obtainable if the time of the radiogenic additions is to be determined.

Conclusion

The majority of the lead samples which have been analysed in this laboratory appear to be of the ordinary type and to have lead isotope ratios which fit the abundance-time curves. Leads of this class are believed to have been concentrated from some deep source and to be closely associated with igneous activity. Such ore leads are useful for geochronological purposes because their isotopic constitutions are related to the time of concentration and deposition of the ore. Anomalous leads, on the other hand, have apparently received contributions of radiogenic lead derived from crustal rocks. If the variations in isotopic composition which are introduced are sufficiently large, they may be used to determine an upper limit to the time of addition of the radiogenic lead and therefore an upper limit to the age of deposition of the lead mineral. A comparison of the anomalous leads from Sudbury with those from the Tri-State deposits indicates that these additions of radiogenic lead may take place on vastly different scales, and possibly through very different processes. Theories of ore deposition which are advanced to explain the origin of ores, such as those of the Tri-State district, must take into account the presence of the radiogenic component and the observed variation in isotopic composition throughout the deposits.

The existence of this anomalous class of lead ores may provide a physical criterion for differentiating the magmatic type of ores which have come from depth from the sedimentary ores which have been associated in disseminated form with near-surface rocks for some period of time before deposition. The authors hope that examination of many more lead samples may provide a better understanding of the genesis of ore deposits and thus be of assistance to economic geologists and the mining industry.

Acknowledgments

The authors are grateful to Professor J. T. Wilson for his assistance throughout this research, and to N. B. Ivory of Noranda Mines, R. H. McConnel of the Bunker Hill and Sullivan Mining Company, and J. P. Lyden of Tri-State Mines for their co-operation in supplying the galena samples.

Financial assistance from the National Research Council, the Geological Survey of Canada, the Research Council of Ontario, and Imperial Oil Limited is gratefuly acknowledged.

REFERENCES

Allan, D. W., Farquhar, R. M., and Russell, R. D. (1953). Science, vol. 118, p. 486.

Alpher, R. A. and Herman, R. C. (1951). Phys. Rev., vol. 84, p. 1111.

Brown, H., Blake, W. J., Chodos, A. A., Lowalkowski, R., McKinney, C. R., Neurerburg, G. J., Silver, L. T., and Uchiyama, A. (1953). Paper presented at Geol. Soc. Amer. meetings, Nov., 1953.

Collins, C. B., Farquhar, R. M., and Russell, R. D. (1952). Phys. Rev., vol. 88, p. 1275.

Collins, C. B. and Freeman, J. R. (1951). Trans. Royal Soc. Canada, Series III, vol. 45, Sec. IV, p. 23.

Collins, C. B., Russell, R. D., and Farquhar, R. M. (1953). Can. J. Phys., vol. 31, p. 402.

Geiss, J. (1954). Zeit. f. Naturforschung, vol. 9a, p. 218.

Keevil, N. B. (1944). Am. Jour. Sci., vol. 242, p. 309.

——— (1950). Am. Mineralogist, vol. 35, p. 816.

Kerr, P. F. and Kulp, J. L. (1952). Science, vol. 115, p. 86.

Kulp, J. L., Owen, H. R., Eckelman, W. R. and Bate, G L. (1953). Columbia University, NYO-6197.

Nier, A. O. (1938). Jour. Am. Chem. Soc., vol. 60, p. 1571.

Nier, A. O., Thompson, R. W., and Murphey, B. F. (1941). Phys. Rev., vol. 60, p. 112.

Russell, R. D., Farquhar, R. M., Cumming, G. L. and Wilson, J. T. (1954). Trans. Am. Geophys. Union, vol. 35, p. 301.

Senftle, F. E. and Keevil, N. B. (1947). Trans. Am. Geophys. Union, vol. 28, p. 732.

Vinogradov, A. P., Zadorozhnyi, I. K., and Zykov, S. I. (1952). Dokl. Akad. Nauk. SSSR, vol. 85, p. 1107.

TRANSACTIONS OF THE ROYAL SOCIETY OF CANADA
VOLUME XLVIII : SERIES III : JUNE, 1954
SECTION FOUR

Ages of Some African Minerals

By P. E. F. GRETENER, R. M. FARQUHAR, and J. T. WILSON, F.R.S.C.

THE earliest studies of the Canadian Shield showed that structure and petrology varied in different regions and attempts were made using these data to subdivide it into provinces (for summaries see M. E. Wilson, 1941; H. C. Cooke, 1947). After Ellsworth (1932) and Nier (1939, 1941) had made a few dozen age determinations they were used to date and to define better the principal provinces (Gill, 1948, 1949; J. T. Wilson, 1949, 1952; Jolliffe, 1952).

During the last three years the ages of over two hundred radioactive and lead minerals from the Canadian Shield have been determined at the University of Toronto (Collins *et al.*, 1954; Russell *et al.*, 1954; Cumming *et al.*, in press). These ages confirm the pattern already discerned. There has, in fact, been good agreement about the broad features of the Canadian Shield among those who have studied it, and the results of these latest measurements have led to some fundamental conclusions regarding Canadian Precambrian geology. By analysing forty-five specimens from Africa the authors have attempted to show that the same basic principles may hold for other continents.

It would be misleading to suggest that all these conclusions about the Precambrian are as yet generally accepted. Most of the age determinations are so recent that they are not widely known and some of those published have been unreliable; consequently most field geologists have an open mind on the conclusions indicated. Meanwhile they continue to follow old conventions but there is undoubtedly a widespread feeling that ideas about the Precambrian need much revision. What is important, is that those who have critically examined the new data agree in the general trend of their ideas. These ideas have encountered justifiable caution but little opposition.

The first part of the paper reviews the physical methods involved in the age determinations listed in Tables I, II, and III. The second part includes a brief account of the new interpretation of the geology of the Canadian Shield and a discussion of the application of the general principles already developed to some of the Precambrian areas of Africa.

Methods of Age Determination

The Common Lead Method or Lead Ore Method

Table I contains the age determinations carried out by this method:

TABLE I

Isotopic Ratios and Estimates of Age for Galenas

No.	Tor. No.	Location	Pb^{206}/Pb^{204}	Pb^{207}/Pb^{204}	Pb^{208}/Pb^{204}	Age 10^6 yrs.	Source
1	193	Rosetta Mine, Barberton, S. Africa	12.65	14.27	32.78	2860 ± 60	1
2	616	Kokosho Mine, N. of Bondo, N. Blg. Congo	12.81	14.39	32.84	2790 ± 90	2
3	593	Midland Farm, Belingwe, S. Rhodesia	13.62	14.95	33.67	2450 ± 120	3
4	392	Vein in Kambui Schists, Sierra Leone	14.01	15.15	34.37	2260 ± 120	4
5	592	Leopard Mine, Lower Gwelo, S. Rhodesia	14.02	15.10	34.14	2270 ± 120	3
6	395	Risks Mine, Kakamega, Kenya	14.05	15.05	34.21	2220 ± 130	3
7	393	Borderland Mine, Busia, Uganda	14.05	15.10	34.24	2220 ± 130	3
8	596	Wanderersrest Mine, S. Rhodesia	14.06	14.99	33.68	2300 ± 130	3
9	500	Vein cutting Masaba granite, Uganda	14.15	15.21	34.20	2200 ± 120	5
10	594	Dona West Mine, Umtali, S. Rhodesia	14.40	15.45	34.39	2100 ± 160	3
11	191	Doornhoek, Marico Distr., S. Africa	15.19	15.50	35.28	1740 ± 200	1
12	396	Copper Queen Mine, S. Rhodesia	15.39	15.50	35.17	1660 ± 200	3
13	615	Zambula Mine, Kibali, N.E. Belg. Congo	16.18	15.63	36.06	1250 ± 260	2
14	188	Stavoren, Groblerstal Dist., S. Africa	16.19	15.53	36.31	1220 ± 260	1
15	189	Groenvlei, Potgietersrust Dist., S. Africa	16.26	15.89	36.64	1170 ± 270	1
16	622	Lubi Camp, Kasai, Belgian Congo	17.52	15.86	37.73	+	2
17	621	Near Kamituga, Kivu, E. Belg. Congo	17.78	15.85	37.53	+	2
18	373	Abenab, S.W. Africa	17.96	15.88	38.69	+	6
19	197	Bamba Kilenda, Lower Congo	18.14	15.92	38.48	+	2
20	623	Mt. Homa, Ituri, N.E. Belg. Congo	18.18	15.92	38.33	+	2
21	198	Hapilo, Lower Congo, Fr. Equat. Africa	18.22	15.98	38.54	+	2
22	196	Kengere, S. Katanga, Belg. Congo	18.22	15.91	38.27	+	2
23	394	Broken Hill, N. Rhodesia	18.25	15.97	38.92	+	3
24	624	Mulungwishi, S. Katanga, Belg. Congo	18.26	15.87	38.49	+	2
25	625	Tsumeb Mine, S.W. Africa	18.32	15.88	38.66	+	3
26	617	La Mia, near Matadi, Lower Congo	18.32	15.84	38.01	+	2

TABLE I (*Cont'd.*)

ISOTOPIC RATIOS AND ESTIMATES OF AGE FOR GALENAS

No.	Tor. No.	Location	$\frac{Pb^{206}}{Pb^{204}}$	$\frac{Pb^{207}}{Pb^{204}}$	$\frac{Pb^{208}}{Pb^{204}}$	Age 10^6 yrs.	Source
27	618	Kisinga, near Muika, N. Katanga, B. Congo	18.35	15.96	38.06	+	2
28	192	E. Geduld Mine, Witwatersrand, S. Africa	18.48	16.32	35.00	Anomalous*	1
29	190	Langlaagte, Pietersburg. Dist., S. Africa	18.51	16.33	39.29	+	1
30	195	Kipushi, S. Katanga, Belg. Congo	18.52	15.97	38.38	+	2
31	597	Kitaka Mine, N.W. of Mbarara, Uganda	19.67	16.40	38.51	Anomalous	3
32	619	Up. Fungwe Riv., Centr. Katanga, B. Congo	20.48	16.11	38.87	Anomalous	2
33	163	Witwatersrand, S. Africa	58.94	24.10	40.19	Anomalous*	7

+These ratios indicate ages younger than 800 million years which cannot at present be precisely dated by this method.

*The Pb^{208}/Pb^{204} ratio for number 28 indicates an age between 1500 and 2000 million years, but since it appears that radiogenic Pb^{206} and Pb^{207} have been added in anomalous amounts to it and in much larger amounts to number 33, this age cannot be regarded as certain.

In 1938 and 1941 Nier published the isotopic composition of twenty-five lead ores. Lead ores contain four isotopes: Pb^{204}, Pb^{206}, Pb^{207}, and Pb^{208}. From his results it was apparent that the isotopic composition of lead in lead ores varied with the age of deposition of the ores, and that younger ores contained more of the last three isotopes. These three are identical with the stable end-products of the radioactive decay of U^{238}, U^{235}, and Th^{232}. It seems probable, therefore, that the change in the isotopic composition of lead with time is a consequence of the continuous addition of radiogenic lead. It is easy to understand how this could take place, because igneous rocks, from which ores are supposed to be derived, commonly contain a few p.p.m. of uranium, thorium, and lead.

Nier's results were first used by Holmes (1946, 1947) in order to derive an age for the earth's crust. Further interpretations were made (Bullard and Stanley, 1949; Collins *et al.*, 1954; Houtermans, 1953), some of which used more experimental data. It was also shown by Houtermans and others that it is possible with certain assumptions to calculate the age of most lead ores from their isotopic compositions. Such lead ores are called normal and can readily be distinguished from the few which have anomalous isotopic compositions. In this paper the curves calculated by Allan *et al.* (1953) have been used to date the samples. These curves are based on the following assumptions:

(*a*) Before the formation of the earth's crust, uranium, thorium, and lead were distributed uniformly throughout the earth's mantle.

(*b*) The lead existing at the time (t_0) when the crust of the earth was formed had a certain isotopic composition and is called primeval lead.

(*c*) During geological time the isotopic composition of this primeval lead has been continuously altered by the addition of radiogenic lead produced by the decay of U^{238}, U^{235}, and Th^{232}. This was the only process to alter the isotopic composition of lead during geological time.

(*d*) The variations of U^{238}, U^{235}, and Th^{232} with respect to lead in the source from which normal lead ores have been derived are negligible.

(*e*) When a normal lead ore is formed the lead is completely separated from any source of uranium and thorium. No further addition of radiogenic lead takes place and the isotopic composition of the lead ore is therefore representative of the time (t_m) of its formation.

These assumptions used by Allan *et al.* involve two geological problems which require explanation. If one believes in the growth of continents during geological time there was no unique time (t_o) for the formation of the crust as assumed in (*b*); the materials of which the crust was gradually built must have come from some shallow depth within the mantle and the mantle probably was formed quickly. It is this time of formation of the upper mantle to which t_o would then refer.

This explanation then makes the fourth assumption (*d*) a reasonable one. The quantities of uranium, thorium, and lead have been measured for many rocks from the crust and are known to vary widely, but recent work suggests that no such variation occurs in the mantle (Ross, Foster and Meyers, in press). The isotopic evidence indicates that assumption (*d*) is indeed valid; it could not be valid if the crust was the source of lead ores. This implies that lead ores, like crustal rocks themselves, are being derived from the mantle. This would not conflict with the field evidence that ores are often emplaced at the same time as igneous intrusions if both came together.

The curves of Allan *et al.* are obtained from the following formulae:

$$t_{206} = \frac{1}{0.154}\log_e\left(\frac{28.97 - X_m}{10.52}\right).10^9 \text{ yrs.}$$

$$t_{208} = \frac{1}{0.0499}\log_e\left(\frac{74.94 - Z_m}{36.54}\right).10^9 \text{ yrs.}$$

Every age given in Table I has been determined as a mean value from the two ratios Pb^{206}/Pb^{204} (X_m) and Pb^{208}/Pb^{204}(Z_m). The Pb^{207}/Pb^{204} ratio has not been used because little change in this ratio has occurred during the greater part of geological time.

The common lead method has the advantage over the U/Pb methods that it is based on a much more abundant element. The common lead method appears to give reliable results for very old specimens. On the other hand, for leads less than 1000 million years old, the possible error in age becomes very large and samples younger than 800 million years have therefore not been dated by the authors. As the number of available isotopic analyses of common leads is now increasing very rapidly it is hoped that it will be possible to increase the accuracy of the method and to lower this limit in the near future.

Some of the specimens given in Table I have been called anomalous (Russell *et al.*, 1954). This term is reserved for those minerals which show an isotopic composition that indicates a complex history, i.e. a history that does not fit our simple assumptions. Specimens 31, 32, and 33 show a Pb^{206}/Pb^{204} ratio which is very much higher than for all other young samples. We must assume that these ores have been in contact with a source very rich in uranium and our assumption (*d*) is therefore not justified. Specimen 28 shows a Pb^{208}/Pb^{204} ratio which is fairly low in comparison with the other two ratios. This might be an old ore which has been derived from a source unusually high in uranium or it might be an old ore which later has been reworked and to which pure uranium lead was added. Here obviously our assumptions (*d*) and (*e*) do not hold, but it would be surprising if all ores fitted the curves because it is well known that the processes of ore formation are complicated. However, the composition of the majority of ores suggests that most of them were derived directly from a uniform source and it is believed that this source was the earth's upper mantle.

The Pb^{207}/Pb^{206} Method

Table II contains the age determinations carried out on uranium- and thorium-bearing minerals. Most of the ages have been determined by the well-known formula:

$$\frac{Pb^{207}}{Pb^{206}} = \frac{1}{137.7}\frac{(\epsilon^{0.9722t} - 1)}{(\epsilon^{0.1537t} - 1)}.$$

The main objection put forward against this method is the possibility of radon loss. Radon, a gas, is an intermediate decay product in the U^{238}-Pb^{206} series and has a half life of 3.82 days. It has been suggested (Kulp *et al.*, 1954) that this half life might be sufficient to allow a partial escape of the radon. This would change the ratio Pb^{207}/Pb^{206} and increase the age determined by this method. Recent unpublished results by Russell have shown that the error should be insignificant for old and unaltered samples.

Whenever a chemical analysis of the minerals was available age values have been determined from the ratios U^{238}/Pb^{206}, U^{235}/Pb^{207}, and Th^{232}/Pb^{208}. The authors are in full agreement with Holmes (1954) that the best age determinations which are available at the present time are those where the three chemical and the Pb^{207}/Pb^{206} determinations give consistent values. In future it will also be possible to use the ratio Pb^{210}/Pb^{206} and radon loss measurements as additional checks.

The Potassium-Argon Method

The single specimen mentioned in Table III has been dated by this method (Shillibeer *et al.*, in press). It is based on the fact that naturally occurring potassium contains about 0.0119 per cent of the isotope potassium 40 which is unstable and decays to calcium 40 by β-emission and to argon 40 by K-electron capture. Since calcium 40 is the main isotope of

TABLE II

ISOTOPIC RATIOS AND ESTIMATES OF AGE FOR RADIOGENIC LEADS

No.	Tor. No.	Location	Mineral	Lead Abundances: Measured 204	Measured 206	Measured 207	Measured 208	Radiogenic 206	Radiogenic 207	Radiogenic 208	207/206 in %	Age (10^6 yrs.)	Source
1	397	Pope Mine, Salisbury, S. Rhodesia	Microlite	0.26 ±.03	73.85	15.19	10.72	70.37	11.35	2.01	16.13 ±0.50	2510 ±100	3
2	162	Witwatersrand, S. Africa	Uraninite	0.05 ±.008	84.78	11.57	3.61	81.83	10.37	1.60	12.67 ±0.50	2070 ±100	7
3	497	Voandelaka, Madagascar	Euxenite	0.14 ±.005	73.95	6.53	19.40	71.52	4.36	14.18	8.08 ±0.12	645 ±60	8
4	112	Kalongwe, Belg. Congo	Pitch-blende	0.035 ±.115	93.90	5.76	0.32	93.76	5.62		5.99 ±0.04	615 ±20	2
5	543	Sierra Leone, B.W. Africa Lat. 8° 49′ N, Long. 11° 48′ W.	Monazite (Alluvial)	0.047 ±.005	9.24	2.51	88.20	8.59	1.81	86.61	21.0 ±3.0	2930 ±200	4

Six other isotopic analyses of radiogenic leads from Shinkolobwe have already been published by us. The range of ages from 612 to 655 x 10^6 years agrees with Nier's results.

These age values have been calculated using the constants

$$(U^{238}) = .153(7) \times 10^9 \text{ yrs}^{-1}$$
$$(U^{235}) = .972(2) \times 10^9 \text{ yrs}^{-1}$$
$$U^{238}/U^{235} = 137.7$$

common calcium (97 per cent) which is very abundant in nature, this branch of the decay is not very suitable for age determinations because of the large corrections for common calcium. On the other hand, the argon 40 content of rocks is negligible under normal conditions and hence this mode of decay meets the requirements for a reliable age method.

TABLE III

A^{40}/K^{40} RATIO AND ESTIMATE OF AGE FOR A POTASSIUM-BEARING MINERAL

No.	Tor. No.	Location	Mineral	$\frac{A^{40}}{K^{40}}$	Br. ratio	Age 10^6 yrs.	Source
1	1084A	Pope's Claim, Salisbury S. Rhodesia	Lepidolite	0.269	0.089	2610	3

Sources of Specimens listed in Tables I, II, and III

1. L. T. Nel, Director, Geological Survey of South Africa, Pretoria.
2. L. Cahen, Musée Royal du Congo Belge, Tervuren, Belgium.
3. A. M. Macgregor, Director (retired), Geological Survey of Southern Rhodesia, Salisbury.
4. N. W. Wilson, Geological Survey of Sierra Leone, Freetown.
5. K. A. Davies, Uganda Development Corporation, Limited.
6. J. G. Dennis, Department of Geology, Columbia University, New York.
7. C. F. Davidson, Geological Survey of Great Britain, London.
8. Ward's Natural Science Establishment, Rochester, New York.

The daughter element in this case is a gas, which may suggest similarities to the well-known helium method. As the latter has been shown to give unreliable results in many cases it is important to draw the reader's attention to the following basic differences between the two methods. Helium is emitted with an energy of approximately five million electron volts (Mev.) which shatters the minerals. In contrast to this argon is emitted with a recoil energy of only thirty electron volts. Further, in uranium-bearing minerals, eight helium atoms are formed as secondary products during the decay of a U^{238} atom to a Pb^{206} atom, so that in addition to the Pb a large amount of helium is produced. This gives rise to very high internal pressures in the crystals and these with the shattering allow migration of the helium. In comparison only a small number of argon 40 atoms is formed in potassium-bearing minerals ($K^{40}/K = 0.0119$ per cent; $A^{40}/Ca^{40} = 0.089$) and these simply replace decayed K^{40} atoms. The argon 40 is probably present in the form of single atoms located in the irregularities of the crystal lattice and is thus easily retained in the crystal. A loss of the gaseous daughter element which made the helium method unreliable should not be expected in the potassium-argon method. This has been confirmed by several experimental checks.

The ages given in Table III have been determined using the following formula and constants:

$$t = \frac{1}{(1+R)\lambda_\beta} \log_e \left\{ 1 + \frac{(1+R)}{R} \frac{A^{40}}{K^{40}} \right\}$$

$$R = 0.089$$

$$\lambda_\beta = 0.503 \times 10^{-9} \text{ yrs.}^{-1}$$

R is the so-called "Branching Ratio" and the new values of this constant has been determined in two laboratories independently. It is extremely difficult to establish this constant and hence slight modifications are possible.

The method is still in an experimental stage and up to the present time has primarily been restricted to minerals rich in potassium such as potassium feldspar and mica (about 10 per cent). There is, however, no difficulty in making age determinations on specimens with a lower content of potassium such as that found in granites. Great possibilities are thus open to the geologists because for the first time a really abundant element can be used for age determinations. The reliability of age determinations on granites by this method has yet to be proved.

Preliminary Geological Interpretation of Age Determinations carried out on Some African Minerals and Comparison to the Precambrian Geology of Canada

The Canadian Shield

The numerous age determinations carried out on minerals from the Canadian Shield (Collins *et al.*, 1954; Cumming *et al.*, in press) and geological field studies in the same area suggest the following results (Wilson, 1951, and in press):

1. The Archean-type rocks of the Canadian Shield can be subdivided into several provinces each of which can be distinguished from its neighbours by differences in general petrology and structure. Within each province all the pegmatites were formed during only one period which lasted a few hundred million years. In each province no veins were formed earlier than the pegmatites but some were formed contemporaneously with them and some at later dates down to the present. For example in the Grenville Province dates of formation of minerals in pegmatites range from 0.8 to 1.1×10^9 years and veins were formed from 1.1×10^9 years ago until quite recently.

2. The two oldest of these provinces (Keewatin Province north of Lake Superior and the Yellowknife Province in the Northwest Territories) are both well over 2000 million years old and have been called "Continental Nuclei." The rocks and structures of these regions are significantly different from other provinces. Clastic sediments (Timiskaming type) overlying basic volcanics (Keewatin type) are the predominant rock types. The ratio of volcanics to sediments is higher than in other areas. Well-differentiated sediments such as limestones and quartzites are scarce or lacking. The sediments and volcanics are arranged in narrow sinuous belts. Between these belts are ovoid batholiths of granite. Gold mineralization in quartz veins is economically important (Pettijohn, 1937).

3. Between and around these continental nuclei lie younger belts which contain abundant gneissic rocks and pegmatites. The Grenville Province is a typical representative of these younger belts.

4. Regarding the age determinations it has been shown that vein minerals

give only lower limits for the age of a geological province. Veins obviously can be very much younger than the geological province in which they occur.

5. This subdivision of the Archean-type rocks of the Canadian Shield given above would seem to support strongly the idea that continents have grown during geological time.

6. Patches of Proterozoic-type rocks are scattered about the Shield. They commonly are infaulted on the inner side of gneissic belts. These rocks are of many different ages and some are older than Archean belts elsewhere (*Leith et al.*, 1935).

The subdivisions of the Canadian Shield so far recognized and the range of age for the different provinces are given in Figure 1.

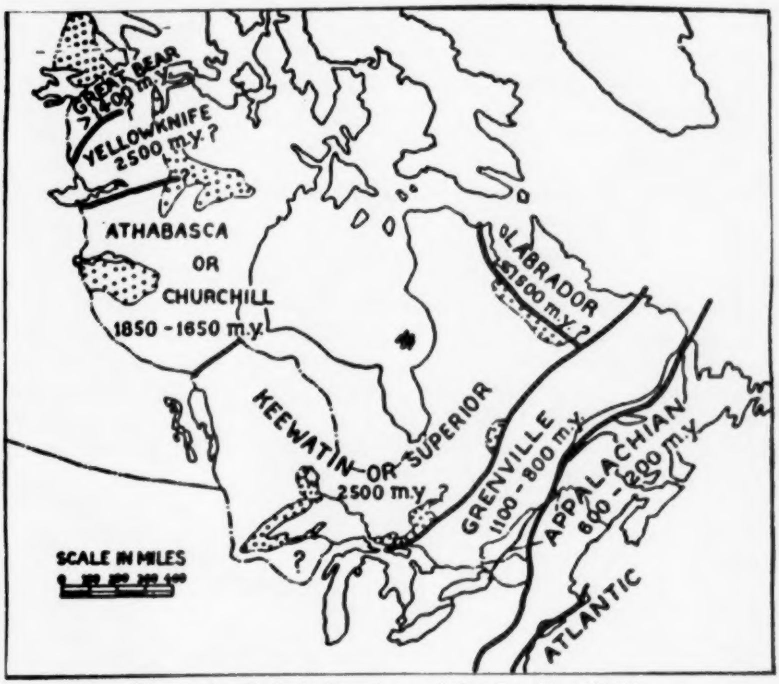


FIGURE 1.—Geological provinces of the Canadian Shield.

The Precambrian in South and Central Africa

In Tables I, II, and III all age determinations carried out on African minerals at Toronto up to May, 1954, are listed. In this paper these determinations have been used together with those published by others (Ehrenberg, 1953; Geiss, 1954; Holmes, 1949, 1950, 1951, and 1954; Bannister and Horne, 1950; etc.). We have had no experience with the rubidium-strontium method, but papers published about it seem to suggest that it is

still in a state of development. Because of apparent differences in some of the ages determined by that method from ages determined by other methods and because of a personal letter from Nicolaysen we have used Rb-Sr ages with caution (Ahrens, 1949 and 1952; Ahrens and Macgregor, 1951; Nicolaysen *et al.*, 1953).

We should like to acknowledge our indebtedness to those geologists who have furnished us with specimens and most of our scanty knowledge of African geology. We regret that this is still very inadequate, but it seemed desirable to publish our new age determinations and make those comparisons with Canadian geology which seemed obvious.

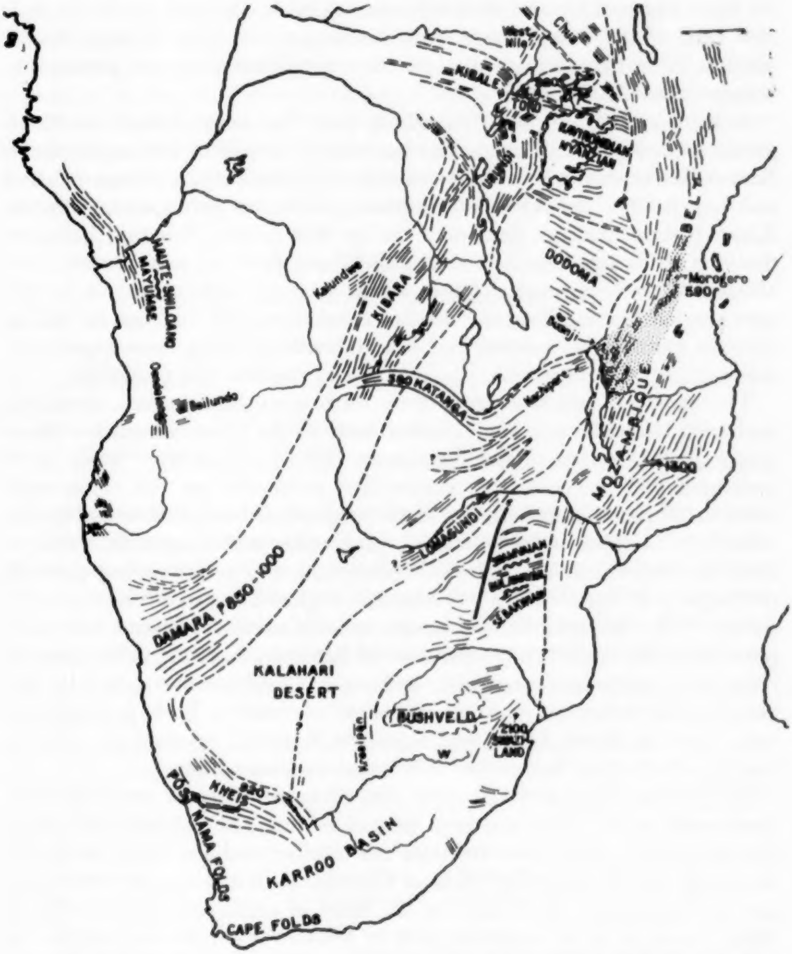
(*a*) *The Continental Nuclei*

In Figure 2 a tectonic map of Southern Africa after Holmes (1951) is given. The best dated area on this map is without doubt the Rhodesian Shield. The age determinations in the region of the Shamvaian, Bulawayan, and Sebakwian systems lie in the range 2100–2660 million years. Three determinations by Holmes (1954) which lie around 2600 million years confirm our own measurements. Both agree with Ahrens and Macgregor's (1951) work. Three determinations were made on minerals from the Kavirondian Belt in Uganda and Kenya. All show ages close to 2200 million years. No age determinations have been made from the area of the Dodoma Belt. A determination on a galena from the western part of Southern Rhodesia in the region of the Lomagundi System gives an age of 1660 million years. It is therefore probable that two nuclei exist, one in Southern Rhodesia and one in Uganda-Taganyika-Kenya separated by the Lomagundi-Mafingi System. This system is shown as an area of Proterozoic-type sediments and paragneisses on the map of Southern Rhodesia (Macgregor, 1946). As no age determinations from the critical area are available the relation between the two old areas mentioned above cannot be fixed at the present time. The new age determinations from Uganda-Kenya and Southern Rhodesia are summarized in Table IV.

TABLE IV

AGES OF MINERALS FROM THE RHODESIAN AND UGANDA-KENYA SHIELDS

Location	Mineral	Author	Age in 10^6 years
Ebonite Cl., Bikita, S. Rhod.	Monazite	Holmes	2680 ± 30
Jack Tin Cl., North of Salisbury, S. Rhod.	Monazite	Holmes	2650 ± 10
Irumi Hills, N. Rhod.	Monazite	Holmes	2620 ± 10
Pope Mine, Salisbury, S. Rhod.	Lepidolite	Toronto	2660 ± 200
Pope Mine, Salisbury, S. Rhod.	Microlite	Toronto	2510 ± 100
Belingwe, S. Rhod.	Galena	Toronto	2450 ± 120
Wanderersrest Mine, S. Rhod.	Galena	Toronto	2300 ± 120
Lower Gwelo, S. Rhod.	Galena	Toronto	2270 ± 120
Dona West Mine, S. Rhod.	Galena	Toronto	2100 ± 160
Risks Mine, Kakamega, Kenya	Galena	Toronto	2220 ± 130
Borderland Mine, Busia, Uganda	Galena	Toronto	2220 ± 130
Masaba, Uganda	Galena	Toronto	2200 ± 130



Correction: Nachipere (N.E. end of L. Nyasa) should be Mafingi. The Nachipere rocks are south of L. Nyasa.

FIGURE 2.—Tectonic map of southern Africa. After A. Holmes.

In the Swaziland-Transvaal region there appears to be another nucleus or part of the Southern Rhodesia nucleus where Holmes (1951) and ourselves have determinations of 2100 and 2860 million years respectively. In the field some of the volcanic and sedimentary rocks in that area appear strikingly like those in the Keewatin and Yellowknife provinces of Canada.

A separate nucleus has been found to exist in Sierra Leone. Three age determinations by different methods carried out on minerals from intrusives into the Kambui Schists all suggest an age of more than 2000 million years

for these schists. This nucleus is separated from the Atlantic Ocean by narrow belts of the Rokell River and Kasila systems (and Tertiary coastal plain). These systems have not yet been dated but they are presumably younger than 2000 million years.

A further high age of 2790 million years has been determined for a galena from Northern Congo. The specimen comes from the region of the Banzyville Formation. On the tectonic map of the Belgian Congo (Cahen and Lepersonne, 1951a) this formation is shown as corresponding to the Kibali System. An age determination for this system, however, indicates that it is of the same age as the Urundi-Kibara Belt (see next section), i.e. about 1100 million years. At the present time age determinations in this area are too few to allow any definite conclusions. All that can be said is that the existence of another nucleus in Northern Congo seems probable but more age determinations are required to confirm this possibility.

The structures and rock types of the African nuclei described above are similar to Keewatin and Timiskaming rocks of the Canadian nuclei. Macgregor (1951) writes of the Bulawayan System as follows: "Basic lavas associated with breccias and interbedded sediments are the commonest rocks in all larger belts." In the same publication he describes the Shamvaian as: "A thick series of arkoses, greywackes and conglomerates overlying the Bulawayan volcanic rocks unconformably in the central parts of the larger gold belts." N. W. Wilson (Geological Survey of Sierra Leone) states: "The Kambui Schists consist mainly of metamorphic lava and pillow lava but include a central zone of banded ironstones, tuffs, agglomerates and pelitic and psammitic sediments. Conglomerates occur in this zone but limestones and pure quartzites are uncommon. Early precambrian schist belts in Sierra Leone and Southern Rhodesia are narrow, sinuous and surround ovoid batholiths." (Personal communication.)

Thus in summary it would seem that there are three or more separate continental nuclei in the southern part of Africa. The volcanics and sedimentary schists within them resemble one another and also closely resemble Keewatin and Timiskaming rocks of Canada. It should also be noted that not all continental nuclei occur in the heart of continents. In this respect Africa is not alone as a nucleus exists in Western Australia and another in Mysore State in India.

The peculiar characteristics of those earliest Precambrian rocks are thought to be due to higher temperature gradients existing in the earth at that time and partly due to the fact that the atmosphere was then without free oxygen (Urey, 1952).

(*b*) *The Younger Belts*

The eastern side of the Uganda-Kenya, Rhodesian, and Swaziland nuclei is flanked by the Mozambique Belt. Our age determination from this region (645 million years) carried out on a euxenite from Madagascar is in good agreement with several other measurements (Ehrenberg, 1953;

Holmes, 1949; Bannister and Horne, 1950). A late Precambrian age of 500–700 million years is now well established for this belt (Table V). Not only the age but also the rock types as seen in the field by one of the authors appear to be very similar to those found in the Grenville Province of the Canadian Shield. Holmes (1951) gives the following description of the Mozambique Belt: "The dominant rocks were found to be biotite-gneisses and migmatites, with sparing occurrences of infolded schists, marbles and amphibolites, together with later granites and pegmatites."

TABLE V

Ages of Minerals from the Mozambique Belt

Location	Mineral	Author	Age in 10^6 years
Voandelaka, Madagascar	Euxenite	Toronto	645 ± 60
Uluguru Mtns., Mozambique	Uraninite	Williams, Ehrenberg	av. 620
Morogoro, Mozambique	Uraninite	Holmes, Nier	av. 620
Mavuzi, Mozambique	Davidite	Bannister *et al.*	565

On the western side of the Uganda-Kenya Shield Holmes has traced the Urundi-Kibara-Damara-Kheis Belt from northwest Congo to southwest Africa (see Figure 2). One of our determinations from northeast Congo in the area of the Kibali Belt would suggest that this belt is of the same age as the Urundi-Kibara Belt. The four age determinations from this region are given in Table VI. It is obvious that many more age determinations in this region are required before a definite geological interpretation can be attempted. So far it seems that the age of the Kibali-Urundi-Kibara Belt lies in the range 900–1300 million years.

TABLE VI

Ages of Minerals from the Kibali-Urundi-Kibara-Kheis Belt

Location	Mineral	Author	Age in 10^6 years
Zambula Mine, Kibali, B. Congo	Galena	Toronto	1250 ± 260
Mitwaba, B. Congo	Galena	Geiss	1150 ± 70
Kagodi, Uganda	Uraninite	Holmes *et al.*	av. 955
Gordonia, S. Africa	Uraninite	Holmes *et al.*	av. 1050

The connection of the Urundi-Kibara Belt with the Damara-Kheis Belt in southwest Africa is so far only suggested by one age determination. This has been carried out on an uraninite from Gordonia in the Kheis Belt. The average age found for this uraninite is 1050 million years.

The Rhodesian nucleus is separated from the Urundi-Kibara Belt by the Lomagundi System for which an age determination has suggested an age of 1660 million years. Other old belts of gneisses may exist between and around the several nuclei. At present we do not know how many there are.

Their elucidation is obviously a major problem in African geology. If there are several such belts some of them must be small, whereas the evidence suggests that the Mozambique Belt is large and continuous. The possibility is thus emphasized that the Kibali, Kibara, Damara, and Kheis rocks may form either one belt or several belts. The literature (e.g., Cahen and Lepersonne, 1951b, and Thoreau, 1951) suggests that pegmatites are common in parts of these belts and hence suitable material for age determinations should be readily available.

For several samples from eastern Congo the isotopic composition indicates a very young age. This, however, is not surprising when it is remembered that many of these specimens are vein minerals. Often the very young age of these minerals was suggested by the donor in advance. As these are not from pegmatites the country rocks may be older.

By comparing these results for Africa with the principles which we derived for the Canadian Shield we can draw the following conclusions:

1. In Africa as in Canada the Archean and Proterozoic types of rocks may be divided into provinces of different ages.

2. In both continents the oldest provinces are more than 2000 million years old. These nuclei have the same lithology and structure wherever found and they are markedly different from all later rocks. This seems to be true for the Kalgoorlie nucleus in Western Australia, the Mysore nucleus in southern India, and probably for the Sveco-Fennidian nucleus of Europe also. Similar nuclei are to be expected in South America and Asia. The two predominant rock types or assemblages may be called Keewatin type (= Bulawayan type) and Timiskaming type (= Shamvaian type). Compared with Canada Africa seems to have more and smaller continental nuclei whose dates tend to be a little older and which contain more ultrabasic rocks, but in both continents gold-quartz veins are economically important in the Keewatin-type belts. It is suggested that these nuclei were formed when the earth was hotter by a different process of mountain-building from that which has prevailed since and that erosion in a reducing atmosphere failed to break up the feldspars giving rise to the Timiskaming (Shamvaian) type of sediments.

3. The existence of younger gneissic belts with similar characteristics to those in Canada is indicated. All are less than 2000 million years old.

4. Associated with the gneissic belts and generally on their inner sides are belts of Proterozoic types of rocks. These are believed to be of many different ages ranging from 2000 million years and younger.

5. Vein minerals, unlike pegmatites, give only lower limits for the age of a geological province and hence they may be much younger than the rocks in which they occur.

Table VII gives a preliminary comparison of the dated Precambrian provinces in North America and in south and central Africa.

The limited number of age determinations so far carried out on African

TABLE VII

DATED PRIMARY OROGENIC PROVINCES IN NORTH AMERICA AND AFRICA

Time in 10^6 yrs.	North America	South and Central Africa
	Cordilleran Province	
500	Appalachian Province	Cape Province
		Mozambique Belt
1000	Grenville Province	
		Kibali-Urundi-Kibara Belt
1500	Great Bear Province	
	Labrador Province	
		Lomagundi System?
	Athabasca Province	
2000		
		Kavirondian Belt (Uganda, Kenya)
	Keewatin and	Kambui Schists (Sierra Leone)
	Yellowknife Provinces	Rhodesian Shield
2500		Banzyville Formation (N. Congo)
		Swaziland (N. Transvaal)
3000		

minerals indicates that the same basic principles have governed Canadian and African Precambrian geology.

ACKNOWLEDGMENTS

This paper would not have been possible without the great amount of help and advice we have received from many African geologists. We should like to thank all those who provided specimens and also F. Dixey, A. Holmes, J. D. Louw, B. F. J. Schonland, P. G. Gane, and E. S. Willbourn. Conversations with H. C. Urey and Harrison Brown helped to clarify our ideas on the origin of the Timiskaming type of sediments.

This research has been assisted by grants from the National Research Council of Canada, Geological Survey of Canada, Research Council of Ontario, and Imperial Oil Limited.

REFERENCES

AHRENS, L. H. (1949). Bull. Geol. Soc. Amer., vol. 60, p. 217.
——— (1952). Trans. Am. Geophys. Union, vol. 33, p. 193.
AHRENS, L. H. and MACGREGOR, A. M. (1951). Science, vol. 114, p. 64.
ALLAN, D. W., FARQUHAR, R. M., and RUSSELL, R. D. (1953). Science, vol. 118, p. 486.
BANNISTER, F. H. and HORNE, J. E. T. (1950). Mineral Mag., vol. 29, p. 101.
BULLARD, E. C. and STANLEY, J. P. (1949). Suom. Geodet. Lait. Julk, Ver des Finn. Geodat. Inst., no. 36, p. 33.
CAHEN, L. and LEPERSONNE, J. (1951a). Atlas General du Congo. Brussells, K. Belgisch Koloniaal Inst.
——— (1951b). Int. Geol. Congress, 18th sess., Great Britain, Rept., pt. 14, p. 61.

Collins, C. B., Farquhar, R. M., and Russell, R. D. (1954). Bull. Geol. Soc. Amer., vol. 65, p. 1.
Cooke, H. C. (1947). Geol. Surv., Canada, Geol. Series, no. 1, 3rd ed., p. 16.
Cumming, G. L., Wilson, J. T., Farquhar, R. M., and Russell, R. D. (in press). Trans. Geol. Soc. Canada.
Ehrenberg, H. F. (1953). Z. Physik., vol. 134, p. 317.
Ellsworth, H. V. (1932). Geol. Surv., Canada, Econ. Geol. Series, no. 11.
Geiss, J. (1954). Z. Naturf., vol. 9A, p. 218.
Gill, J. (1948). Structural geology of Canadian ore deposits, p. 20. Can. Inst. Min. Met.
——— (1949). Trans. Royal Soc. Canada, Series III, vol. 43, Sec. IV, p. 61.
Holmes, A. (1946). Nature, vol. 157, p. 680.
——— (1947). *Ibid.*, vol. 159, p. 127.
——— (1949). *Ibid.*, vol. 163, p. 453.
——— (1951). Int. Geol. Congress, 18th sess., Great Britain, Rept., pt. 14, p. 254.
——— (1954). Nature, vol. 173, p. 612.
Holmes, A., Leland, W., and Nier, A. O. (1950). Am. Jour. Sci., vol. 248, p. 81.
Houtermans, F. G. (1953). Nuovo cimento, vol. 10, p. 1623.
Jolliffe, A. W. (1952). Int. Geol. Congress, 18th sess., Great Britain, Rept., pt. 13, p. 141.
Kulp, J. L., Bate, G. L., and Broecker, W. S. (1954). Am. Jour. Sci., vol. 252, p. 345.
Leith, C. K., Lund, R. J., and Leith, A. (1953). U.S. Geol. Surv., Prof. Pap. 184.
Macgregor, A. M. (1946). Provisional geological map of Southern Rhodesia and Tati Concession, rev. ed. Salisbury, Southern Rhodesia, Geol. Surv. Office.
——— (1951). Int. Geol. Congress, 18th sess., Great Britain, Rept., pt. 14, p. 111.
Nicolaysen, L. O., Aldrich, L. T., and Doak, J. B. (1953). Trans. Am. Geophys. Union, vol. 34, p. 342.
Nier, A. O. (1938). Jour. Am. Chem. Soc., vol. 60, p. 157.
——— (1939). Phys. Rev., vol. 55, p. 158.
——— (1941). *Ibid.*, vol. 60, p. 112.
Pettijohn, F. J. (1943). Bull. Geol. Soc. Amer., vol. 54, p. 925.
Ross, Foster, and Meyers (in press).
Russell, R. D., Farquhar, R. M., Cumming, G. L., and Wilson, J. T. (1954). Trans. Am. Geophys. Union, vol. 35, p. 301.
Shillibeer, H. A. and Russell, R. D. (in press). Can. Jour. Phys.
Thoreau, J. (1951). Int. Geol. Congress, 18th sess., Great Britain, Rept., pt. 14, p. 282.
Urey, H. C. (1952). The planets, p. 149. Yale University Press.
Wilson, J. T. (1949). Trans. Can. Inst. Min. Met., vol. 52, p. 231.
——— (1952). Trans. Am. Geophys. Union, vol. 33, p. 195.
Wilson, M. E. (1941). Geol. Soc. Amer., 50th Anniv. vol., p. 271.

TRANSACTIONS OF THE ROYAL SOCIETY OF CANADA
VOLUME XLVIII : SERIES III : JUNE, 1954
SECTION FOUR

Temperature and Heat Flow within the Earth

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Presented by J. T. WILSON, F.R.S.C.

THE temperature and heat flow at depths greater than a few kilometres within the Earth cannot be determined experimentally, and comparatively few attempts have been made to derive quantitative values theoretically. Although the main features of the Earth's interior (e.g., that it is solid to a depth of 2900 kilometres) have been deduced from a study of earthquake waves, it is by no means certain that these features have remained the same for billions of years in the past, or that the material of the mantle is not capable of very slow motion, as has been suggested by the proponents of the convection-current theory of orogenesis. The mathematical difficulties inherent in obtaining any detailed quantitative results for the temperatures in an Earth-model involving convection are very formidable. Even if the mantle be taken as solid throughout geologic time (and there are good reasons for assuming this), so that the Earth may be considered as cooling by conduction alone, the problem of the temperature distribution and heat flow, allowing for the radioactive production of heat, is extremely complicated. A solution in a practical form can be obtained only if the thermal conductivity and diffusivity are assumed constant for the material of the Earth. Available evidence on the values of these quantities within the Earth suggests that, although this assumption is not wholly correct, it should apply at least for the upper part of the mantle.

Statement of the Problem

The assumptions made in the model of the Earth and the numerical calculations are as follows:

1. The Earth is solid throughout, and has been so for the past 4×10^9 years.
2. It is spherically symmetric as regards all physical properties.
3. The effects of contraction may be neglected.
4. The thermal conductivity and diffusivity may be treated as constant.
5. The radioactive substances are distributed in spherical shells, in each of which their concentrations are constant.
6. The surface temperature of the Earth has remained at a constant value, 0°C, for the past 4×10^9 years.

The first assumption is not wholly correct, since seismic evidence shows that the Earth has an inner core which is partially liquid. However, the

effect of the liquid part of the core, in which an adiabatic temperature gradient is maintained, will be negligible in the greater part of the solid mantle. 4×10^9 years may seem a high figure for the time since solidification of the Earth, but the accepted value of 3.5×10^9 years, derived from the study of isotopic variations in lead ores, is being revised to 4.5×10^9 years (Russell, 1954), so that even the value used here may be a little low. It is known, again from seismology, that the Earth is spherically symmetric to a high degree of accuracy, apart from the first few tens of kilometres. Since the temperature under a large area of a given crustal structure would be very little different if the entire surface of the Earth were of that structure, the assumption of complete spherical symmetry can be used with confidence. The assumption that the release of gravitational potential energy effected by contraction may be neglected has been proven by E. R. Lapwood (1952). W. D. Urry (1947) and, more recently, R. J. Uffen (1952) have examined the variation with depth of the conductivity and diffusivity. Both find that these increase with depth, the diffusivity, however, doing so fairly slowly. .007 cm^2/sec has been taken as a representative average value for the diffusivity over the first 1000 kilometres, and for the conductivity, the variation of which can be taken into account partially in calculating the heat flow, Uffen's (1952) values have been used. The fifth assumption is not a very restrictive one, since any given distribution can be approximated to by one of the above type. Finally, an investigation of possible variations in the average surface temperature of the Earth has shown that even under the most drastic assumptions it should not have changed by more than $\pm$ 60°C.

The Solution of the Problem

With the above assumptions, the problem can be divided into two parts, viz., the solution for a non-radioactive Earth cooling from a given initial temperature distribution, and the solution for a radioactive Earth heating up from zero temperature. The complete solution is the sum of the two.

The solution for a non-radioactive Earth is classical, having first been given by Fourier (1822). Numerical computations have been carried out, using an initial temperature curve derived from Daly's (1943) values for the melting point in the mantle and Simon's recent (1953) values for the melting point of iron under high pressures such as exist in the core. The values obtained for the heat-flow and temperature at six depths in the Earth and at six times in the past are given in Table I. These results show how slowly temperatures change at great depths. At these depths thermal conditions are not greatly different from their initial values, and a correction can be made for the increase of conductivity with depth in the calculation of the heat-flows. Near the surface, on the other hand, cooling is considerable, and the surface heat-flow after 4×10^9 years is but little affected by the values taken for the initial temperature distribution in the first few tens of kilometres, as has already been pointed out by Urry (1947).

TABLE I

TEMPERATURE AND HEAT FLOW—NON-RADIOACTIVE EARTH

Temperature (° C.)

Time (10⁹ yr) \ Depth (km)	50	100	500	1000	2000	2900
0	900	1380	2310	2856	3615	3958
.25	491	940	2296	2851	3613	3955
.5	409	796	2279	2848	3611	3953
1	328	647	2220	2839	3604	3949
2	256	510	2061	2818	3590	3942
3	220	439	1914	2786	3575	3934
4	197	394	1791	2742	3560	3926

Heat-flow (cals/cm² yr)

Time (10⁹ yr) \ Depth (km)	50	100	500	1000	2000	2900
.25	19.57	18.34	5.33	5.83	4.77	3.72
.5	16.50	16.35	5.69	5.85	4.87	3.82
1	13.36	13.81	7.15	5.86	4.95	3.93
2	10.50	11.15	9.36	6.12	5.04	4.15
3	9.03	9.68	10.27	6.71	5.10	4.33
4	8.09	8.71	10.55	7.44	5.16	4.48

The solution for a radioactive Earth is much more complex. It was first given by G. Comr :ctz, although he never published his derivation, and was used by Urry (1947, 1949) in his calculations of surface heat-flow. Details of the mathematical solution, which is too long to reproduce here, will shortly be published elsewhere (Jacobs, in preparation). The calculations required to obtain numerical values with this solution would have been impossible without the use of an electronic computer. That employed was the Ferranti computer of the Physics Department, University of Toronto.

RESULTS

Results have been worked out so far for two specific models. The first is a simplified one, in which the crust is replaced by a single layer 20 kilometres thick of granite-granodiorite composition, the mantle is identified as dunite, and the composition of the core is taken as that of iron meteorites. Apart from the simplified crustal layer, this model is identical with the one proposed by Bullen (1947). The second model, due to Adams and Williamson (1925), is more detailed. A structure of four 15-kilometre layers is taken for the crust, with the top layer of granite-granodiorite composition, and the remaining three layers of composition changing from acidic to basic. From 60 to 1600 kilometres the material of the mantle is identified

as dunite, and from 1600 to 3000 kilometres it is taken as of the same composition as pallasitic meteorites. The core again is identified with iron meteorites. This model is valuable for two reasons: first, the presence of relatively high amounts of radioactivity to a depth of 60 kilometres gives an indication of what thermal conditions may be like under the oceans, since recent measurements of the heat-flow through the ocean floors by Bullard (1954) and Revelle and Maxwell (1952) suggest that there may be the same total amount of radioactivity beneath both continents and oceans, but extending in high concentrations to greater depths in the case of the latter; second, since the computations have been set up in such a manner that the effect of introducing different concentrations in the same shell can be found relatively easily, the large number of shells used in this model will make it possible to fit the distribution of radioactivity for almost any other type of model which may be proposed later.

It should be noted that, although the literature has been thoroughly examined to determine the radioactive concentrations in the above rock types, and the most representative values have been taken, these values may well have to be changed in the future. For example, only two years ago the concentrations of potassium in ultrabasic rocks were found to have been overestimated by factors of twenty and more. Thus it is important that the

TABLE II

TOTAL TEMPERATURES IN THE MODELS

Temperatures for model I: (° C.)

Time (10^9 yr) \ Depth (km)	50	100	500	1000	2000	2900
0	900	1380	2310	2856	3615	3958
.25	905	1216	2339	2894	3656	3992
.5	861	1166	2361	2930	3693	4024
1	763	1056	2382	2988	3753	4077
2	606	892	2358	3072	3844	4162
3	521	785	2308	3124	3913	4225
4	461	714	2248	3163	3970	4282

Temperatures for model II: (° C.)

Time (10^9 yr) \ Depth (km)	50	100	500	1000	2000	2900
0	900	1380	2310	2856	3615	3958
.25	1447	1520	2330	2885	3643	3985
.5	1424	1576	2346	2910	3667	4010
1	1267	1481	2369	2960	3705	4052
2	997	1245	2383	3017	3763	4117
3	825	1073	2347	3057	3808	4168
4	712	934	2298	3086	3841	4209

TABLE III

TOTAL HEAT-FLOWS IN THE MODELS

Heat-flows for model I: (cals/cm² yr)

Time (10^9 yr) \ Depth (km)	50	100	500	1000	2000	2900
.25	15.1	14.5	5.3	5.8	4.8	3.3
.5	15.2	14.5	5.7	5.8	4.9	3.2
1	14.2	13.8	7.0	5.9	5.0	3.2
2	13.1	13.0	9.1	6.1	5.0	3.3
3	12.3	12.5	10.4	6.7	5.1	3.5
4	11.6	11.8	11.1	7.4	5.1	3.6

Heat-flows for model II: (cals/cm² yr)

Time (10^9 yr) \ Depth (km)	50	100	500	1000	2000	2900
.25	12.0	5.4	5.3	5.8	4.8	3.7
.5	14.8	7.1	5.6	5.8	4.9	3.7
1	16.3	9.5	6.6	5.9	4.9	3.8
2	15.8	11.1	8.2	6.1	5.0	3.9
3	14.7	11.2	9.3	6.6	5.0	4.0
4	13.7	11.0	10.9	7.2	5.1	4.2

method of calculation used here will easily allow correction for any such change.

The total temperatures and heat-flows obtained for the two models are given in Tables II and III. A number of interesting features are immediately evident. For example, in spite of the extremely low concentrations of radioactivity in the deep mantle and core, there is still a heating-up of two or three hundred degrees. Near-surface conditions appear to have been greatly different in the far past from those existing at present, and indeed, for the second model, in which the region of high radioactivity penetrates to 60 kilometres depth, the results indicate that there may even have been remelting of the material at depths of from 50 to 100 kilometres during the first billion or so years. However, this brief temperature rise at the very beginning soon ceases and cooling commences. The rate of cooling, for both models, was greater in the past than it is now, and this suggests that orogenetic activity may have decreased with time, and perhaps have been caused by different processes in the far past. The present temperatures at 50–100 kilometres differ by as much as 200° C. for the two models, and this suggests that similar differences may hold beneath the oceans and continents. Interpretation of the heat-flow results is not so obvious, but it is interesting to observe that the present values near the core boundary are of the order of magnitude required by Bullard's (1950) "dynamo" theory of the origin of the Earth's magnetic field, though a little smaller numerically.

The present surface heat-flow for the two models can readily be calculated from these results. The value obtained for model I agrees well with observed values, although that for model II is somewhat higher, which suggests that too much radioactivity has been included in the surface layers of the model. It is, of course, not implied that the temperatures and heat-flows are known to the accuracy given in Tables II and III. The extra figures have been retained in the computations in order to facilitate comparison of the results at different depths and times in the Earth's history.

Conclusions

In conclusion, it should be emphasized that the importance of the work just described lies not so much in the particular results which have just been presented for two Earth-models as in the fact that a general method is now available for examining the thermal properties (so far as conduction theory is concerned) of an Earth-model with any desired distribution of radioactivity. It would be unwise to make any dogmatic statements from the results so far obtained, but they do seem to indicate the following preliminary conclusions:

1. Thermal conditions in the Earth's upper mantle were considerably different four, three, and even two billion years ago from those existing at present. This fact provides an instance of the importance, already emphasized by some geologists (Wilson, 1952), of examining the geological evidence available for the vast extent of Precambrian time with minds unprejudiced by the characteristics of the better-known post-Cambrian periods.
2. Near-surface thermal conditions under the oceans and continents may be quite different.
3. At great depths the Earth has probably been heating up throughout its history. The value of the present heat-flow at depth is mostly dependent on the initial temperature curve. The results found for the distribution used above are not in disagreement with Bullard's theory of the Earth's magnetic field.
4. Preliminary calculations of the amount by which the Earth's radius has decreased by thermal contraction alone show that the contraction possibly does not exceed 10 kilometres. These calculations make no allowance for change of state or for loss of material by vulcanism.

Acknowledgments

The kindness of W. D. Urry in lending his unpublished (1947) manuscript is gratefully acknowledged. Thanks are due also to the National Research Council for a grant paying for computations on the electronic computer, and to the Research Council of Ontario for a scholarship which assisted one of the authors.

REFERENCES

ADAMS, L. H. and WILLIAMSON, E. D. (1925). Smithsonian report for 1923, p. 241.

BULLARD, E. C. (1950). Mon. Not. Royal Astr. Soc., Geophys. Suppl., vol. 6, p. 36.

——— (1954). Proc. Royal Soc., vol. A222, p. 408.

BULLEN, K. E. (1947). Introduction to the theory of seismology. Cambridge University Press.

DALY, R. A. (1943). Bull. Geol. Soc. Amer., vol. 54, p. 401.

FOURIER, J. (1822). Théorie analytique de la chaleur. Paris.

JACOBS, J. A. (in press). The earth's interior; chap. 18, Handbuch der Physik, vol. 47. New ed., Berlin: Julius Springer.

LAPWOOD, E. R. (1952). Mon. Not. Royal Astr. Soc., Geophys. Suppl., vol. 6, no. 6, p. 402.

REVELLE, R and MAXWELL, A. E. (1952). Nature, vol. 170, p. 199.

RUSSELL, R. D. (1954). The age of the earth. Ph.D. thesis, University of Toronto.

SIMON, F. E. (1953). Nature, vol. 172, p. 746.

UFFEN, R. J. (1952). A study of the thermal state of the earth's interior. Ph.D. thesis, University of Western Ontario.

URRY, W. D. (1949). Trans. Am. Geophys. Union, vol. 30, p. 171.

URRY, W. D. and COMENETZ, G. (1947). Thermal history of the earth. Private manuscript.

WILSON, J. T. (1952). Trans. Am. Geophys. Union, vol. 33, p. 195.

TRANSACTIONS OF THE ROYAL SOCIETY OF CANADA
VOLUME XLVIII : SERIES III : JUNE, 1954
SECTION FOUR

Porphyries of the Porcupine Area, Ontario

By E. S. MOORE, F.R.S.C.

Introduction

PORPHYRY has been, since the discovery of gold in Porcupine, a very important rock to the prospector, geologist, and mine operator. As was observed at an early date, a definite relation exists between certain porphyry intrusions and gold ore. The presence in the Porcupine area of older pyroclastics identical in composition to the intrusive porphyry led to considerable confusion because these were considered intrusive porphyry and therefore favourable for the occurrence of gold. The question of their source gave rise to different opinions regarding the ages of intrusive porphyry and, consequently, of the age of the ore deposits. Further, papers have been written indicating that the intrusions formed in place and are syntectic in origin.

The intrusive porphyry and porphyry pyroclastics are remarkable for the exclusive sodic (as contrasted to sodic and potassic) composition of their feldspars. Following the porphyries there were intrusions of albitite on quite a large scale which also contain only sodic feldspars. The granite exposed in the area is not normal granite, but unusually rich in sodic feldspars.

The porphyries of Porcupine are therefore of unusual interest to geologists and indicate a highly sodic petrographic area. The data for this paper were obtained during more than two years of field and laboratory studies and the preparation of a new geological map on a scale of one inch equals 1000 feet. This work was mostly done for McIntyre Porcupine Mines Limited and the writer is indebted to Dr. Balmer Neilly, President of the company, for his generous permission to present this, the second, paper resulting from these studies. He also expresses his gratitude to mine geologists, engineers, mine officials, and others in this famous camp for their co-operation and assistance while the work was in progress. He regrets that space does not permit individual acknowledgment of those who rendered assistance.

Stratigraphy and Structural Geology

A brief description of the major stratigraphic and structural features of the area is essential to a discussion of the nature and origin of the porphyry and related rocks. The series and systems recognized are, in descending order, as follows: Pleistocene—drift, alluvium, and lacustrine deposits;

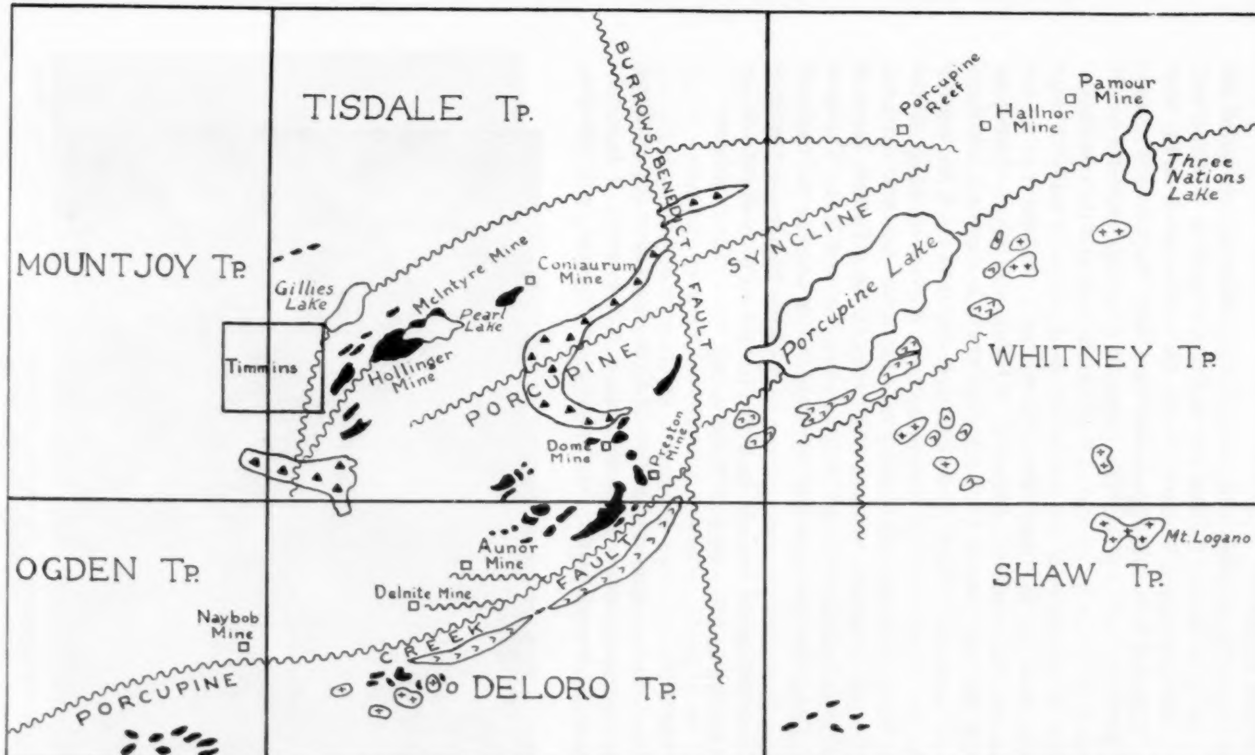
Keweenawan—olivine diabase; Matachewan—quartz diabase, mostly porphyritic; Algoman—granite, porphyry, syenite, albitite, quartz veins, and carbonatized rocks; Haileyburian—basic and ultrabisic rocks largely altered to serpentine-talc-chlorite schists, tremolite, and asbestos; Timiskaming—slate, greywacke, quartzite, conglomerate, Krist fragmental and carbonaceous slate; Keewatin—mainly intermediate lava flows (andesite and dacite and many pillowed variolitic flows) with minor basic and rhyolite flows; basic to intermediate and acid pyroclastics and thin sediments including siliceous iron formation. The Keewatin formations cover the greater part of the area and there is a marked difference in them on the north and south sides of the Porcupine Creek fault.

The structural history of Porcupine has been described in an earlier paper (Moore, 1953). Two major periods of folding have been recognized, one at the close of the Keewatin and the other during the Algoman revolution. The Keewatin lavas were extensively folded at the close of that period and before the deposition of the Timiskaming sediments and pyroclastics. They were again folded to some extent and highly faulted during the second period, in which also the Timiskaming was highly folded. The important Porcupine syncline was mainly developed during the second or Algoman period of folding although there is a good deal of evidence that this large basin structure was initiated at a much earlier date, probably in the Keewatin period.

There are many faults in the area, some of which are outlined on the map (Fig. 1). The largest of these is the Porcupine Creek fault named from Porcupine Creek which follows it for some distance. It can be traced for eighty miles or more and it has had a great influence in shaping the geology of Porcupine. Movement on this great break occurred at several times, the most extensive being in the Algoman period. It seems to have influenced the extrusion of acid rocks in the Keewatin and the basic rocks in the Haileyburian as shown by their distribution. Other large faults traverse the area north of the Porcupine Creek fault from an east-west to a northeast-southwest direction. One large fault, the Burrows-Benedict, cuts across the area nearly north-south and offsets all the others. Hence it is later, but how much is not known. There are numerous smaller faults both thrust and normal and these are pre-ore and post-ore. The large faults striking nearly parallel to the Porcupine syncline are pre-porphyry in age, but some movement on them took place after the intrusion of the porphyry.

Keewatin and Timiskaming Acid Rocks

It is believed that while an immense quantity of intermediate and minor basic rocks was being extruded during the Keewatin, a large granite magma was developing under most, if not all, of the Porcupine area. This magma supplied the acid rocks through time representing at least three systems or series.



Keewatin; acid pyroclastics and rhyolite. Timiskaming; Krist fragmental, exposed and located by drilling.

Algoman porphyries. Algoman granite.

8000' 0 8000'

FIGURE 1.—Sketch map showing the distribution of the main occurrences of acid rocks in the Porcupine area.

Keewatin Acid Rocks

A zone of acid pyroclastics with small rhyolite flows extends across the northeast corner of Deloro, the southern and central parts of Whitney, and into Cody township east of Whitney. Part of this zone is shown on the map (Fig. 1). The rock is mainly agglomerate containing fragments of quartz-feldspar porphyry and rhyolite. The porphyry fragments resemble somewhat those in the Krist fragmental of the Timiskaming, and the two formations might be mistaken for one another in some places. A study of large areas shows, however, that they differ in a number of respects. The formation considered Keewatin is confined to the south side of the Porcupine Creek fault and the Krist to the north side. The Keewatin is much more sheared and impregnated with pyrite and carbonate than the Krist, but the most definite criterion for age determination is the interbanding of the acid pyroclastics with siliceous banded iron formation which is restricted to the Keewatin in all other parts of the Porcupine Area. Further, the acid pyroclastics are interbedded with basic agglomerate and lavas. The porphyry fragments are too much altered to determine whether the feldspars were originally as distinctly sodic as those in the Krist fragmental, but there are sufficient differences between these two formations to justify classifying one as Keewatin and the other as Timiskaming.

Krist Fragmental

This formation was named from the old Krist claims near the southwest corner of Tisdale township where the rock is well exposed. It is mainly restricted to the western part of the Porcupine syncline and its distribution,

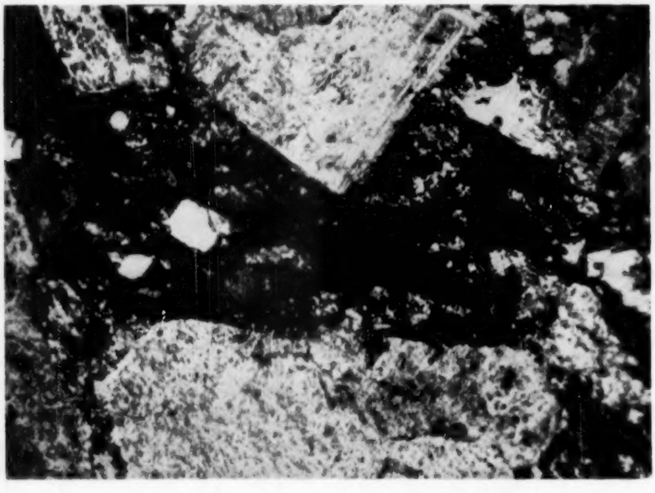


FIGURE 2.—Photomicrograph of phenocrysts in feldspar porphyry fragment from **Krist** fragmental. Crossed nicols, $\times 30$.

as shown by exposures and diamond drilling, is outlined on the map (Fig. 1). It is an agglomerate consisting mainly of feldspar and feldspar-quartz porphyry very similar to the Algoman porphyry intrusives (Fig. 2). For many years it was considered an intrusive porphyry and large sums of money were spent in drilling around its outcrops in the hope of finding gold. It is ironic that this formation is probably the most barren of all formations in the Porcupine camp.

Even after nearly twenty years of mining in Porcupine this rock was confused with the porphyry and on Burrow's map (1924) it is included with the Pearl Lake and other porphyry intrusions. It remained for M. E. Hurst, Provincial Geologist of Ontario, in his work during the early thirties, to recognize its true character, as depicted on his fine areal map (Map 47a, 3rd ed., 1939). Although it consists mainly of fragments of acid porphyry of various sizes up to more than three feet in diameter it also contains fragments of Keewatin greenstone from the lavas through which the vents passed. One of these fragments measures more than three feet in diameter. The Krist fragmental grades into intermediate pyroclastics and contains also fragments of chert and slate.

The Krist fragmental supplied most of the boulders and pebbles to the Timiskaming conglomerate into which it grades in many places by a mingling of water-worn material with angular fragments. Many of the boulders and pebbles have been described as granite, but only a few are granite pebbles and these are not a normal, but a highly sodic, granite.

The similarity of the Algoman porphyry and the Krist fragmental has led to arguments about the number of intrusive porphyry formations in the

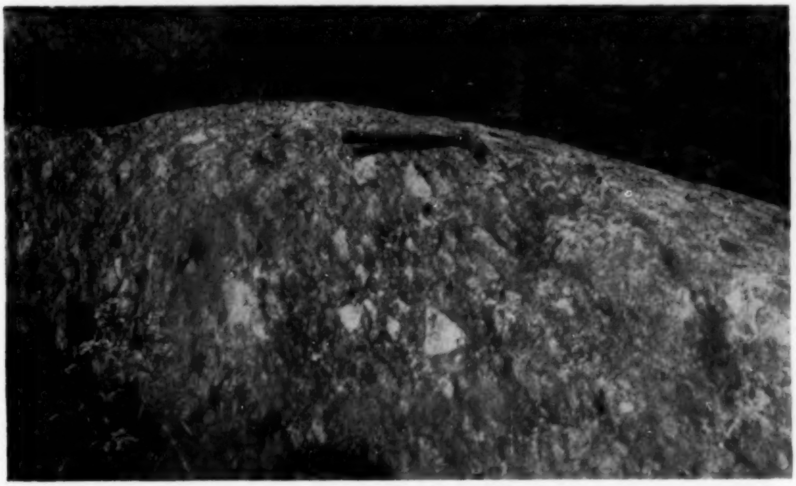


FIGURE 3.—Krist fragmental in south half Lot II, Concession I, Tisdale.

area and the age of the ore deposits. There are no flows or intrusives associated with the Krist fragmental. It lies on a carbonaceous slate or directly on the eroded surface of folded Keewatin lavas at the base of the Timiskaming series. The vents from which it was ejected have not been found. They may be concealed beneath the Timiskaming sediments or occupied by some of the later porphyry intrusions. The formation is not greatly sheared, but it is sericitized and to a small extent is in places albitized.

The Krist fragmental may be explained as originating during the folding at the close of the Keewatin period when part of the granitic magma beneath the Porcupine syncline escaped and rose part way to the surface, but did not reach it. A porphyry was thus formed and when gas pressure later reached a high level this porphyry was blown out in fragments. This type of volcanic activity has been observed in many parts of the world where no strong orogeny occurred.

Algoman Acid Rocks

Although the granite, porphyry, and albitite, and the associated ore deposits, are regarded by most geologists as Algoman in age, this classification has not been accepted by some because these rocks are not known to be in contact with the Timiskaming sediments anywhere in the Porcupine area, except in the Dome mine. Even there the relations have been questioned. However, in recent years, mine workings have exposed a number of contacts which, to the writer, show undoubted cross-cutting relations between Timiskaming sediments and the porphyry considered Algoman. The writer is greatly indebted to T. C. Holmes, Chief Geologist of Dome Mines Limited, for pointing out these exposures.

Porphyries

The porphyry classed as Algoman is widely distributed, but the larger intrusions mostly occur around the western part of the Porcupine syncline, in or near the largest mines (Fig. 1). There is considerable porphyry in Mt. Logano, a large intrusion in the northern part of Shaw township, but an indeterminate part of it is more properly called granite. The porphyry is all intrusive because no flows or pyroclastics have been found associated with it. It is mostly of the feldspar-quartz type with varying proportions of phenocrysts of feldspar and quartz although some intrusions and parts of others have no quartz phenocrysts. The fresh rock almost everywhere shows a distinct porphyry texture with abundant to sparse phenocrysts in a microcrystalline matrix consisting of little but quartz and feldspar. The phenocrysts vary greatly in size, the largest feldspars reaching about 5 mm. in maximum diameter and the quartz being considerably smaller. The feldspars may show distinct crystal borders or be rounded; the quartz phenocrysts are mostly rounded in outline as they are in many porphyries (Figs. 4 and 5). Most of the feldspars are somewhat sericitized and many of them have been crushed and dragged by post-intrusive movements (Fig. 6).

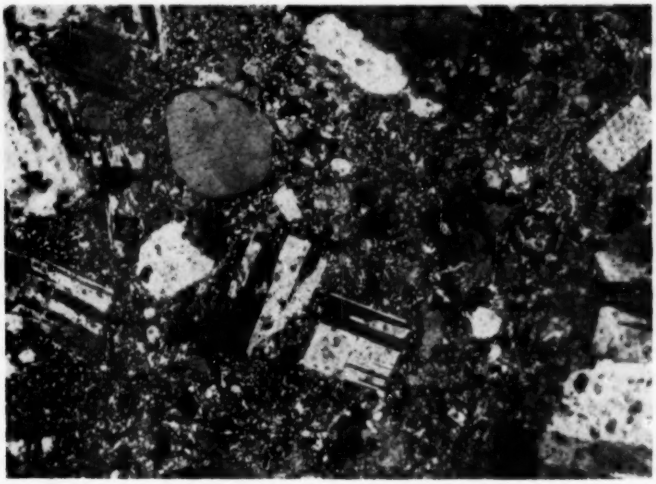


FIGURE 4.—Feldspar-quartz porphyry near contact with slate in the Dome Mine. Crossed nicols, ×30.

The porphyries do not show any physical and chemical change with increasing depth although the intrusions tend to merge at great depth and form a bulwark against crushing, whereas at higher levels the smaller bodies of porphyry have been sheared with the enclosing lavas.

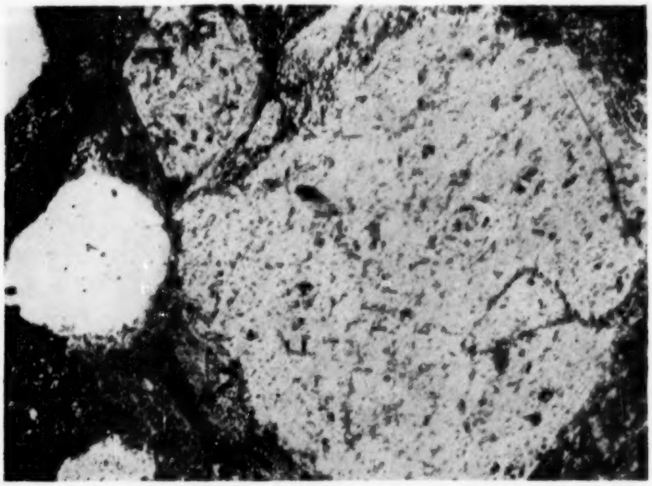


FIGURE 5.—Photomicrograph of feldspar-quartz porphyry with large, somewhat sericitized feldspar phenocryst and a smaller one of quartz. The phenocrysts are undeformed. From the 6825-foot level of the McIntyre mine. Crossed nicols, ×30.

There has been some speculation regarding the occurrence of intrusive porphyry of two ages in this area. In about three hundred thin sections of porphyries studied, two showed two porphyries, one cutting the other. One of the specimens came from the MacKenzie Veteran claims in Tisdale township and the other from Mt. Logano in Shaw township. In each of these sections a finer-grained porphyry cuts a coarser and the finer-grained one is crowded with small phenocrysts. The two rocks have apparently the same composition and they are considered to be from the same source, one being intruded at a little later time than the other.

Porphyry intrusions have been observed in all mines in the camp except those near the east end including Porcupine Reef, Broulan, Hallnor, and Pamour. The nearest Algoman intrusions to these mines have been found in drill cores. They consist of sodic granite and syenite and sodic granite–porphyry which are described later in this paper. No typical porphyry has so far been found.

The Pearl Lake porphyry is the largest intrusion in the area, and the most significant in relation to the origin of ore. It played an important role in the formation of the great ore zone which includes the Hollinger, McIntyre, and Coniaurum mines. It is not considered that the gold came directly from the porphyry as suggested by at least one geologist (Smith, 1948) but the porphyry bodies were important because of the structural control imposed on the migrating ore-bearing solutions. These solutions must have moved up the pitch of the rocks with the Pearl Lake porphyry forming the hanging wall because the great concentration of veins in the Hollinger occurred in an area over which the porphyry lay before a large

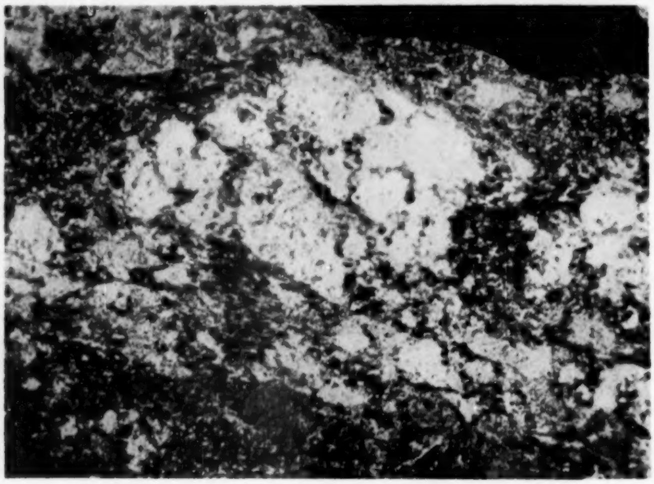


FIGURE 6.—Photomicrograph of large feldspar phenocryst crushed and dragged. McIntyre mine, 6500-foot level. Crossed nicols, $\times 30$.

part of it was removed by erosion. Further, the bulk of the gold on McIntyre has been mined underneath this intrusion and along the north side of it where the intrusion forms the hanging wall dipping steeply southward. It seems probable that part of the ore solutions descended from the base of the porphyry into fractures and shear zones in the rock beneath it as did the silver ores beneath the diabase sill at Cobalt.

The Pearl Lake porphyry has been described by several geologists: Robinson (1923), Langford (1938), and Furse (1948). It is about 5500 feet long, 1800 feet in maximum width, and 5300 feet in its vertical dimension. It strikes N. 78 degrees E. and dips about 84 degrees to the southeast. A prong extends southwest along the Hollinger fault indicating that the porphyry was intruded after the fault was formed. Associated with the Pearl Lake intrusion are several other intrusions which though smaller are still large compared with most of the intrusions in the area. These are the Gillies Lake or Northern, the Miller Lake, Millerton, Crown, Acme, Coniaurum, New Northern, and others. Nearly all show some tendency to coalesce at depth and some join at shallow depths. Apophyses may connect two bodies at one level and they may separate lower down and join up again at a still greater depth. The Acme differs from the others in maintaining its independence although almost surrounded by other bodies of porphyry. The porphyries in the Hollinger mine have been well described by Jones and in the Coniaurum by Carter (1948).

All the porphyry intrusions show a remarkable uniformity in pitch and this pitch corresponds to the pitch of all rocks north of the Porcupine Creek fault that are involved in the Porcupine syncline. In the sediments and lavas this pitch may be measured on pillows, slickensides, fluting, small drag folds, and other features. The porphyry bodies all pitch eastward at angles between 43 and 56 degrees. The Crown porphyry has been traced for 4000 feet and the pitch of the top of the intrusion is between 50 and 56 degrees for this distance.

The porphyry is on the whole less favourable for the occurrence of ore than the lavas or some of the Timiskaming sediments, but it carries a great deal of ore, where fractured, in the northern ore zone and it is very important in some of the mines in the southern zone including the Preston East Dome, the Dome, Paymaster, and Buffalo Ankerite. Particularly in the Preston East Dome some of the large bodies of porphyry have been broken by faulting and are important producers of gold. These porphyries have been described by Hawley and Hart. Those in the Dome have been described by Holmes and those in the Paymaster by Longley (1948).

The Chemical Character of the Porphyry

The highly sodic character of the acid rocks in Porcupine has been mentioned. A series of tests was made to determine whether potash feldspar was entirely lacking in them. The cobalt nitrite method of staining potash feldspars described by Keith (1939) was employed and found to

be satisfactory. It never failed to give the bright yellow stain on any microcline or orthoclase that could be identified in thin sections. Polished chips of rock instead of thin sections were used for the tests because they could be much more easily prepared and if one test did not seem to be satisfactory the chip could be easily repolished for another one. A specimen of normal granite in which microcline and orthoclase were present was used as a standard to test the solution for efficiency in staining. It was found that the stain did not affect any minerals other than potash feldspars. The method does not indicate potash in sericite. It is possible to determine with considerable accuracy the proportions of potash feldspar in a rock by measurement of the stained areas under the microscope.

One hundred and seventy specimens of acid rocks from various parts of the area were tested with the help of G. F. Ennis and with laboratory equipment loaned by W. A. Firth, Chief Assayer at McIntyre. Most of these were porphyries. More than a few small specks of potash feldspar were never found in any specimen of porphyry and nearly all lacked this mineral. The granites were also nearly all unusually low in potash feldspar.

A number of geologists have reported oligoclase and andesine in porphyries from several localities so a considerable number of specimens were gathered from several of the mines and from outcrops in different parts of the area and sent to Professor W. W. Moorhouse of the University of Toronto, a petrographer skilled in using equipment designed for the determination of feldspars. He identified all feldspar in the specimens as albite and some of it as high-grade albite.

This abundance of albite in Canada's greatest gold field is of interest. Tyrrell (1915), nearly forty years ago, called attention to this association of albite and gold, and Gallagher (1940) discussed this relation in a number of gold fields in the Canadian Shield. In spite of the lack of potash feldspar in the acid rocks associated with the gold ore there was, however, an invasion of potash after these rocks were intruded as indicated by the abundance of sericite in many of them, the growth of flakes of muscovite in fringes on pyrite grains in the mineralized zones, and the analyses of mill feed from veins in sericitized porphyry. These analyses very commonly show potash to be more abundant than soda.

A "black" porphyry occurs in the Hollinger and McIntyre mines and in some places near them (Fig. 7). This rock is impregnated with carbon, part of which is graphite. It is found only where the porphyry is altered and so far as observed, never in fresh rock. The carbon may be seen as specks in the phenocrysts, and blackening part, or all, of them. It also occurs as patches or veinlets running through the phenocrysts or matrix. Similar carbon is abundant in some gold veins and it forms veinlets in quartz-carbonate veins. These occurrences indicate that the carbon must have been in a fluid state and very mobile. They also show late deposition of this substance. Its nature and source are a puzzle because of its mobility and because some of it affects the precipitation of gold in cyanide solution and

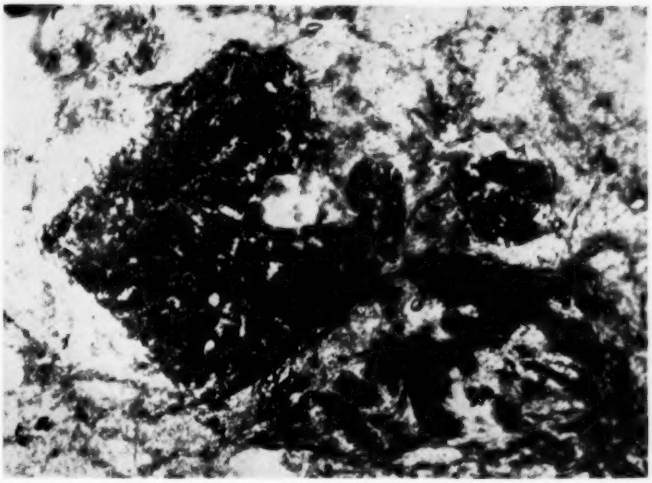


FIGURE 7.—"Black" porphyry from 3875-foot level, McIntyre mine, showing a feldspar phenocryst and part of the matrix impregnated with carbon. Photomicrograph ×30.

some of it does not. There is much graphitic carbon in thin sediments interbedded with the Keewatin lavas and in the carbonaceous slates of the Timiskaming series. Some geologists have considered these as the source of the carbon; others have regarded it as possibly of igneous origin. A relation may exist between the carbon and methane gas which is quite common in the lower part of one mine in which the carbon is most abundant.

Origin and Contact Effects of the Porphyry

The writer and most other geologists who have studied the porphyry consider it as a distinctly magmatic intrusive and the intrusion as largely coincident with folding in the Algoman period. A few geologists have, however, claimed that it is metasomatic in origin. The first to advance this hypothesis was Whitman (1927) and he was followed much later by Evans (1944). Whitman derived much of his support for his hypothesis from the occurrence of what he termed "école" porphyry. This term was applied to patches of light-coloured porphyry fragments in the Keewatin lavas, which Whitman likened to schools of fish. These patches are in the vicinity of larger bodies of porphyry and are supposed to represent the partial development of syntectic porphyry. The term *école* is not a very suitable word since *banc* is the French term for school in "school of fish." It does, however, convey the idea Whitman wished to express and it has been commonly used in Porcupine for the phenomenon discussed. Figure 8 is a photomicrograph of what O. F. Carter, Chief Geologist of Coniaurum mine, considers a good example of Whitman's école. The porphyry fragments indicate crushing of the rock rather than strong reaction between the porphyry and

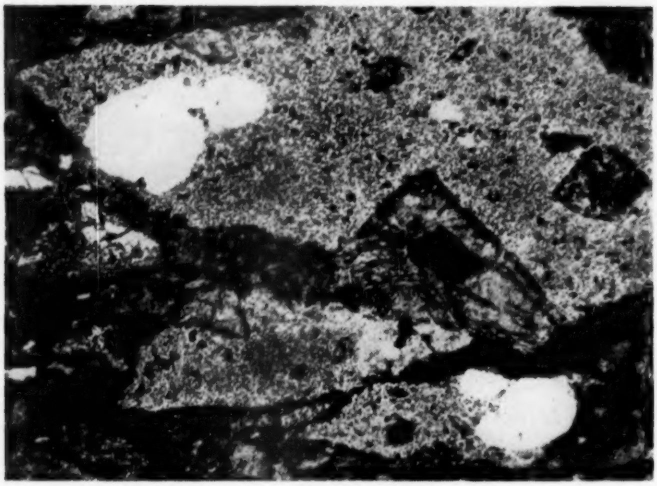


FIGURE 8.—Photomicrograph of "école" porphyry from drill core, 1000-foot level, Coniaurum mine. Fragments of porphyry are embedded in chloritized lava and they show sharp outlines. Crossed nicols, ×30.

lavas. In the Crown porphyry-breccia on the Hollinger many dikelets of porphyry occur in brecciated Keewatin lavas and other small injections occur among the fragments of lavas. Where even minor movements have affected these rocks there are many examples of Whitman's école structure, but the porphyry fragments retain sharp boundaries and show little sign of metasomatic action. The writer feels, after a careful study of this type of structure, that Graton and McKinstry (1933) were correct in explaining it as caused by crushing of small porphyry bodies.

Evans based his claim for syntectic porphyry on the opinion of some petrographers that a rock so rich in albite phenocrysts could not have crystallized directly from a magma, but other features were also considered. He assumed that the porphyry was developed from some pre-existing intrusive less rich in soda, but he did not make clear the nature of this intrusion. It seems to the writer that any process capable of changing all intrusions into a rock similar to the existing porphyry would be an impossibility. Further, in many places the porphyries show sharp contacts with the lavas and sediments and cross-cutting relations are common. Evans claims that the phenocrysts often lie at an angle to the shearing planes and that they must therefore have formed after the shearing occurred. In about three hundred thin sections examined no clear case was found to support this argument. There are frequent examples of rotation of phenocrysts into a 45-degree position with respect to the planes of shear, a feature mentioned by Bain (1933). Hawley has also described this type of rotation of the phenocrysts in the porphyry in the Preston East Dome mine.

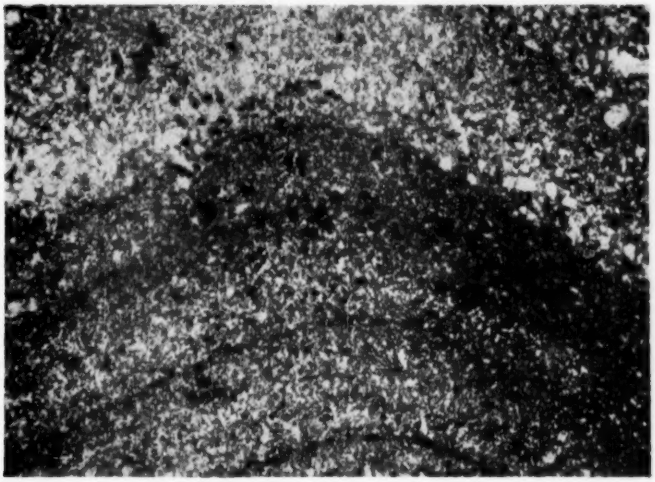


FIGURE 9.—Photomicrograph of slaty greywacke at contact with porphyry in the Dome mine. There is almost no change in the sediment as the contact is approached, except for the introduction of a little carbonate. Crossed nicols, ×30.

Holmes (1944) claimed that sediments in the Dome Mines have been transformed into porphyry-like rock in the vicinity of porphyry intrusions, but an examination of several contacts kindly shown to the writer failed to convince him that the porphyry had altered the sediments to a great extent; in fact specimens taken at and near the contacts and studied in thin section showed practically no alteration (Fig. 9). Possibly, a study of thin sections might have led Holmes to another conclusion.

A study of contact effects over the whole area shows that they are surprisingly small. It is difficult to separate contact and regional metamorphic effects in some places. There was regional carbonatization, steatitization, sericitization, chloritization, and ottrelitization as well as thermal metamorphism near the contacts of porphyry intrusions. The main contact effects on the lavas resulted in chloritization, a low order of metamorphism, sericitization, silicification, and carbonatization. There is evidence in the mines that movements, large or small, occurred along many of the porphyry bodies with a narrow zone containing quartz, chlorite, and carbonate developing along the contact between the porphyry and intruded rocks. In some places there is a zone of mixed brecciated porphyry and lava. Where inclusions of lava are found in the porphyry they have been altered to chlorite.

From the metamorphic effects of the porphyry it is evident that it was not at a very high temperature when intruded. Further, it is believed that most of the phenocrysts were in existence at that time. A number of thin sections show that at some contacts the phenocrysts appear to have been

FIGURE 10.—Photomicrograph of porphyry-lava contact (porphyry white, lava black) on 3300-foot level, McIntyre mine. The lava is highly chloritized. Crossed nicols, ×30.

screened out and left behind while the matrix material proceeded into the walls for short distances. One slide shows a tongue of porphyry injected into lava with several phenocrysts bunched together a short distance from its end, like a log jam in the narrow part of a stream, while the matrix material penetrated some distance into the wall rock. The comparatively low temperature of intrusion also accounts for the lack of prominent chilled borders in many intrusions.

Albitites

An interesting set of albitite dikes is found in Porcupine. They vary in width from about one foot to twenty-five feet and in length from a few yards to over three thousand feet, the longest one seen being in the Hollinger and McIntyre mines. They consist of a grey, holocrystalline rock which in a typical dike is composed almost entirely of albite. There are gradations in the rock towards granite and granite-porphyry especially in the southern part of the area. The gradation is shown by increasing quartz and biotite or muscovite and the development of granitic or porphyritic texture. A little biotite or quartz occurs in most of the dikes, but these minerals are absent in some of the purest albitites. The biotite is commonly altered to chlorite. In some dikes sericite, quartz, chlorite, carbonate, and tourmaline, with a little hornblende, epidote, actinolite, and serpentine have been introduced, the serpentine and, probably, others being developed from inclusions of basic rock. The feldspar in many places shows prominent

FIGURE 11.—Photomicrograph of albitite, somewhat porphyritic, from the Naybob mine. Crossed nicols, ×30.

polysynthetic twinning and interlocking of crystals (Fig. 11); in others the texture is more granular, approaching that of aplite, or granite.

South of the Porcupine Creek fault these dikes are exposed at the surface, but north of it with one possible exception, they occur only under ground in the mines; in the McIntyre below 2250 feet and in the Hollinger below 2600 feet. They increase in number to about the 5500-foot level and a few have been found in the deepest workings. It is probable that more exist in the lower levels but owing to less extensive mine openings they are not exposed.

Most of the dikes are found cutting porphyry intrusions and in some places they show distinct contacts with chilled borders. Where they extend into the lavas the contacts are much less distinct or even indefinite because of albitization of the wall rock. It is suggested that there is a genetic link among the albitites, the quartz-albite-ankerite, quartz-albite-apatite-scheelite-tourmaline, and quartz-fouqueite-axinite veins which preceded the gold veins. A little albitization of the porphyries occurred near the albitite dikes as some of the phenocrysts show some addition of albite, but most of the addition is found in the matrix. There seem to have been three periods of albitization in this area: (1) during the intrusion of the porphyries when the process was widespread, but not very intense, (2) during the intrusion of the albitites, and (3) during the formation of the albite-bearing veins. The last two were quite restricted in area, but intense in some places.

A peculiar feature of the albitite dikes in the McIntyre mine is the occurrence in them of numerous inclusions from a few inches to 18 × 30 inches in diameter. Only small ones have been found in the dikes in the Hollinger

mine. The inclusions are mostly lighter coloured than the dike rock and stand out prominently in the roofs of the mine workings. The first of these inclusions found were about the size and shape of goose eggs and this feature led Langford (1938) to call the rock a "goose egg" dike. Most of the inclusions are angular and many of them show sharp borders. Apparently the rounded ones suffered corrosion and attrition by the dike rock during their ascent from their source to their present location. The inclusions vary somewhat in composition, but they are mainly granite consisting of quartz, microcline, microperthite, albite, oligoclase, and a little biotite. Their composition and location indicate that they were torn loose from a granite body beneath the Porcupine syncline, through which the albitite broke, and were carried up thousands of feet to their present location. It will be observed that the composition of this granite differs somewhat from that of the granites described below.

Granite, Alaskite, Granite-Porphyry, Syenite

There are a number of outcrops of rocks called granite south of the Porcupine Creek fault, where deeper erosion of the Keewatin rocks has exposed them. These are not typical granites because their potash feldspar content is very low. They are high in albite and this highly sodic character is a feature of much of the Algoman granite in the Canadian Shield. These rocks have been called alaskites, but this name is even less suitable than granite because of the paucity of potash feldspars in them. A number were carefully tested for potash feldspars. The maximum content did not exceed 25 per cent and only a few had 15 per cent. There are biotite and muscovite

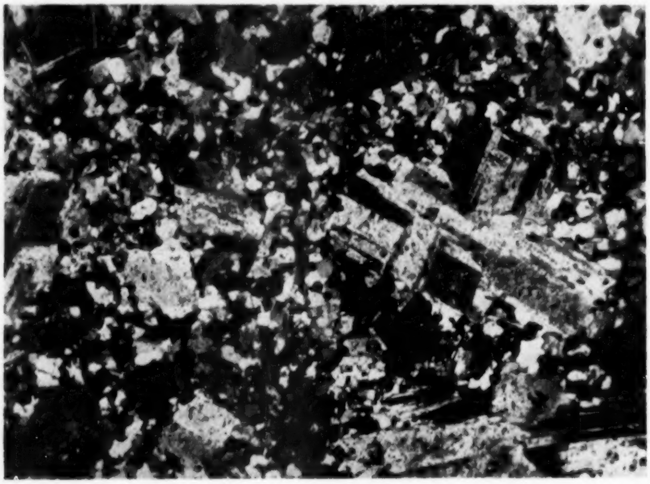


Figure 12.—Photomicrograph of soda granite-porphyry from drill core taken near the southwest corner of the Broulan property. Crossed nicols, ×30.

varieties, and some with hornblende and epidote, but these minerals are regarded as introduced constituents. The quartz and muscovite were formed late and this feature seems to be reflected in the frequent occurrence of networks of quartz stringers and barren veins in the granite intrusions, and in the formation of muscovite in some veins in the ore zones.

Soda granite seems to be the most suitable name for the granitic rocks. There is also some soda granite-porphyry (Fig. 12) and soda syenite. There is no outcrop of these rocks north of the Porcupine Creek fault, but soda granite-porphyry was cut by a drill near the southwest corner of the Broulan claims, and soda granite and syenite were also found in cores taken a short distance north of the northwest corner of Porcupine Lake. The writer is indebted to Nelson Hogg, formerly resident geologist for the Ontario Department of Mines in Porcupine for these specimens. These rocks are the only Algoman intrusives reported north of the Porcupine Creek fault in the east end of the Porcupine camp.

The highly sodic character of the granitic rocks indicates direct links among the granite magma, the Krist fragmental, the Algoman porphyries and albitites, and, finally, the gold-quartz veins in this area.

REFERENCES

BAIN, G. W. (1933). Wall-rock mineralization along certain Ontario gold deposits; Econ. Geol., vol. 28, pp. 705–43.

BURROWS, A. G. (1924). The Porcupine gold area; Ont. Dept. Mines, vol. 33, pt. 2.

Can. Inst. Min. Met. (1948). Symposium: Structural geology of Canadian ore deposits, pp. 442–65. This work contains excellent articles on the individual mines in the Porcupine area by thirteen mine geologists.

EVANS, J. E. L. (1944). Porphyry of the Porcupine district, Ontario; Bull. Geol. Soc. Amer., vol. 55, pp. 1115–52.

GALLAGHER, D. (1940). Albite and gold; Econ. Geol., vol. 35, pp. 698–736.

GRATON, L. C., MCKINSTRY, H. C. *et al.* (1933). Outstanding features of Hollinger geology; Trans. Can. Inst. Min. Met., vol. 36, pp. 1–20.

HOLMES, T. C. (1944). Some porphyry-sediment contacts at the Dome Mine, Ontario; Econ. Geol., vol. 39, pp. 133–41.

KEITH, M. L. (1939). Selective staining to facilitate Rosiwald analysis; Am. Min., vol. 24, pp. 561–5.

LANGFORD, G. B. (1938). Geology of the McIntyre mine; Amer. Inst. Min. Met. Engs., Tech. Pub. no. 903, pp. 1–19.

MOORE, E. S. (1953). The structural history of the Porcupine gold area; Trans. Royal Soc. Canada, Series III, vol. 47, Sec. IV, pp. 39–53.

ROBINSON, H. S. (1923). Geology of the Pearl Lake area, Porcupine district, Ontario; Econ. Geol., vol. 18, pp. 753–71.

TYRRELL, J. B. (1915). Note on the geology of Porcupine; Bull. Can. Min. Inst., June, pp. 397–8.

WHITMAN, A. R. (1927). Syntectic porphyry at Porcupine; Jour. Geol., vol. 35, pp. 404–20.

TRANSACTIONS OF THE ROYAL SOCIETY OF CANADA
VOLUME XLVIII : SERIES III : JUNE, 1954
SECTION FOUR

A Theoretical Approach to the Calculation of Seismic Wave-Velocity in Sedimentary Formations

By N. R. PATERSON

Presented by J. T. WILSON, F.R.S.C.

SEISMIC wave-velocities in rocks have been measured for many years. In earthquake seismology the practice started shortly before 1900 and a large amount of data has since been collected in all parts of the world. Since seismic exploration for petroleum started in earnest in 1925, literally millions of velocity determinations have been made and many of these data are no longer considered confidential. The determinations were made originally in order to convert from time intervals to distances and to correct for time delays in the surface or weathered layers. It was not until about 1935 that interest centred on the velocities themselves and it was realized that here was a very powerful tool for studying the nature of the earth's crust. This interest has grown rapidly and developed along several different lines.

Geologists hoped that accurate velocity measurements would tell them something about the petrology of the rocks in which the waves travelled. In an isotropic medium the longitudinal and shear velocities are simple functions of Young's modulus, the bulk modulus, and the density. If the density were known could not the elastic properties be calculated and facts concerning the lithology be deduced? It soon became apparent that the earth's crust does not behave everywhere as an isotropic medium and furthermore that pressure and temperature are variables which profoundly influence the elastic constants. Studies of rock samples in the laboratory revealed that changes in porosity, permeability, texture, and pore-filling material have a much greater effect on the elasticity of the rock than do changes in mineralogy. Much work has been carried out to investigate these effects and it is continuing at the present time. Names such as Zisman, Ide, Birch, Bancroft, Hughes, and West are prominent in the literature which describes these studies. An excellent review by Krumbein (1951) outlines the many geological uses to which velocity information can be put. These include better understanding of sedimentary environments and facies, and of post-depositional changes such as lithification, metamorphism, and depth of burial. Velocity logging is also discussed and the dependence of velocity on depth of burial is shown to strongly recommend this type of logging where "time-rock units" are required.

Exploration geophysicists have been interested in rock velocities chiefly for their value in correcting seismograms and in making depth-maps. A velocity as a velocity is a very useful thing. If velocity-depth relations could be established even over limited areas the need for costly and time-consuming velocity surveys would be reduced and seismic interpretations improved. A vast number of the field data have been studied and some important conclusions reached. The supposition that velocity increases linearly with depth is only true for limited distances within rocks of one lithological group. For entire geological sections, however, velocity appears to increase as the one-sixth power of the depth (Z) and as the one-sixth power of another parameter (R_t) involving chiefly porosity and cementation.

$$V = 1948\,(R_t)^{1/6}Z^{1/6} \tag{1}$$

The parameter (R_t) has been expressed by Faust (1953) as a function of resistivity alone. This interdependence seems somewhat fortuitous in the light of the laboratory work mentioned earlier. Furthermore, the effect of mud infiltration on the measured resistivity is considerable and indeed fairly large errors can always be expected with the normal well-logging procedure. Nevertheless, the theory has been applied with success to basins with widely differing sedimentary sections. Figure 1 is a correlation chart comparing calculated and measured times for short intervals of depth using this Faust velocity-depth relation. The mean deviation is 0.0145 seconds.

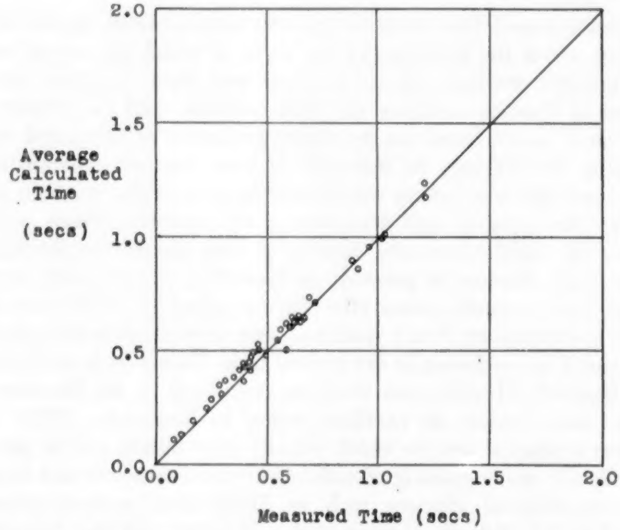


FIGURE 1.—Times for different depth intervals in fifty wells with wide geographical distribution, compared with times calculated by means of Equation (1). (After L. Y. Faust, 1953.)

It is hoped that with the aid of a more easily evaluated lithological parameter and adequate geological control, velocities may soon be determinable over large areas and to great depths by means of very shallow core-hole surveys.

Physicists have long been interested in the behaviour of elastic waves in anisotropic media. Experimental work was not attempted chiefly because of the extreme difficulty of constructing media of suitable degree of anisotropy. Early seismological results did not point to the earth as being significantly anisotropic. Jeffreys (1929) remarked that igneous rocks should be almost perfectly isotropic. Studies by Hodgson (1953) on the Canadian Shield confirm this supposition. Before long, however, exploration seismologists noted a marked transverse isotropy in some sedimentary rocks. McCollum and Snell (1932) conducted some field experiments and described how the difference between vertical and horizontal velocities could be used to aid in seismic exploration. Byerly (1938) suggested that certain anomalous events observed in the California earthquake of July 6, 1934, pointed to double refraction in the surface layers of the earth. Stonely (1949) used the classical wave theory to predict the behaviour of seismic waves in a transversely isotropic earth. The chief drawback to these studies has been the difficulty of evaluating the elastic constants for anisotropic media, especially such difficult media as are found to comprise the upper layers of the earth. Without knowledge of these constants we can do little to test the conclusions of the wave-theory.

What was clearly needed was a theoretical model of structure close to that of sedimentary rocks and simple enough to be susceptible to physical and mathematical treatment. Such a model was found in the geological literature in the systematic packing of spheres. Graton and Fraser (1935) made an exhaustive study of such packings and concluded that rounded sand grains deposited by normal sedimentary processes should within certain restrictions form assemblages wherein the packing is predominantly of the hexagonal rhombohedral type. Examinations of sands and sandstones tended to confirm this conclusion. Iida and Ishimoto did considerable experimental work in the years 1936 to 1939 on spherical packings and further emphasized the usefulness of these models to simulate sand formations. Iida (1939) went so far as to measure vertical velocities at low frequencies in such packings and to relate them to depth and to other parameters including size, porosity, and moisture content. Figure 2 shows that he too found a sixth power relation between velocity and depth of burial. Fritz Gassman (1951), following the theory of Hertz and Hara, made the first rigorous study of the elasticity of spherical packings. His results include expressions for velocity as a function of Young's modulus ($\hat{E}$), the density ($\hat{\rho}$), and the Poisson's ratio (ν) of the spheres, the bulk modulus and the density of the pore-filling material, and of course, the pressure or depth of burial (Z). For dry packings the velocity is found to vary as the one-sixth power of the depth and as the one-sixth power of a parameter involving

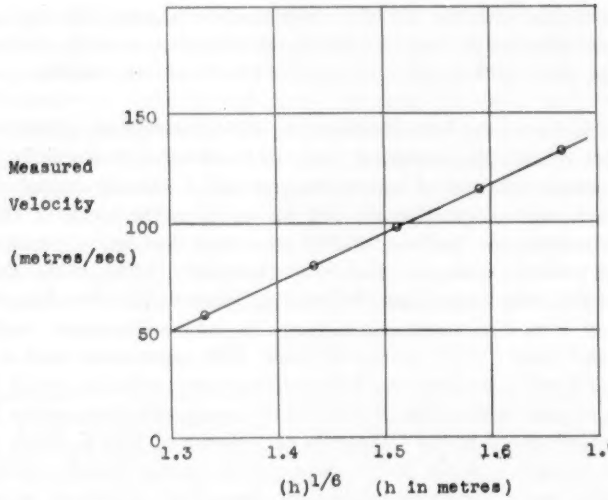


FIGURE 2.—Velocity of standing compression wave in column of lead spheres, compared with the sixth root of the height (h) of the column. (After K. Iida, 1939.)

the elastic constants and the densities. The vertical compressional velocity in a dry hexagonal packing is (after Gassman),

$$V = 860 \left[\frac{2\pi \hat{E}^2 g}{(1 - \nu^2)^2 n^3 \hat{\rho}} \right]^{1/6} Z^{1/6} \qquad (2)$$

where n is the porosity of the medium and g the acceleration due to gravity. It is rather amazing that this purely theoretical treatment should have arrived at a result so similar to that which Faust obtained (see Equation (1)) from a statistical study of field data. White and Sengbush (1953) applied Gassman's equations to an actual sand deposit and found excellent agreement with the measured velocities for the vertically travelling wave. An example of this is shown in Figure 3. An expression similar to Equation (2) but involving an extra term was used for depths below the water table.

The writer's present work is concerned with testing the theory for different packings of glass spheres in the laboratory, simulating changes in depth by varying the vertical pressure on the spheres. Preliminary results agree within the experimental error with the law of increase of velocity with depth. Figure 4 compares compression velocities measured for horizontal propagation in a "chance" packing (after Graton) with theoretical velocities for a hexagonal packing calculated by means of formulae similar to Equation (2). The displacement of the experimental curve from the theoretical compression curve (V_2) and the difference in slopes are believed to be due to several experimental conditions which do not satisfy the assumptions made by the theory. First, the packing, being of the "chance" type,

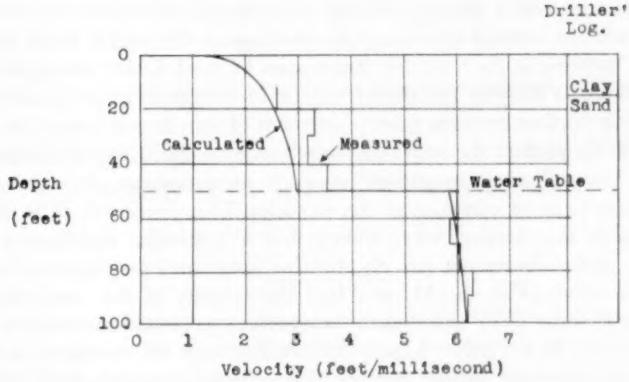


FIGURE 3.—Velocity log of shot-hole drilled in loose sand, Henderson County, Texas, compared with compression velocity calculated by means of Equation (2). (After J. E. White and R. L. Sengbush, 1953.)

is likely to have only half its volume in the form of hexagonal "colonies," and these "colonies" are not necessarily uniformly oriented. Thus a discrepancy in slope is to be expected. Secondly, Gassman's assumption that the medium being dry acts as an "open" system, or one in which the elastic constants are unaffected by the presence of air in the pores, may not hold at the fairly high frequencies employed. This would lead to a small vertical

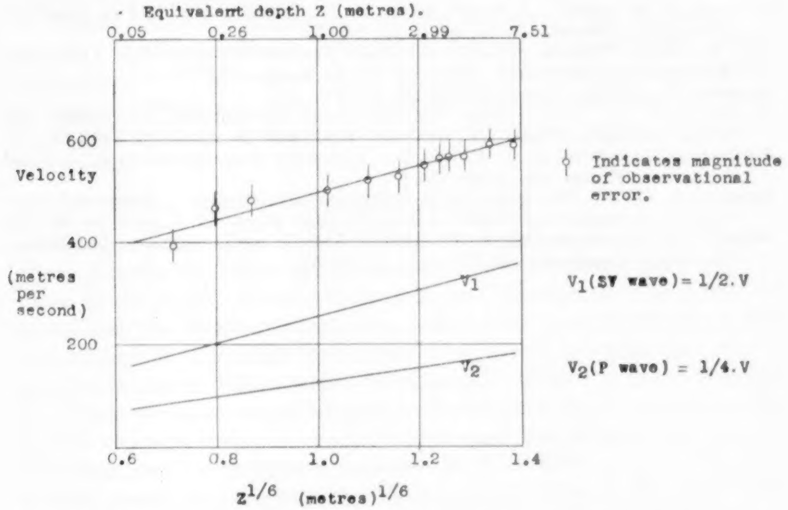


FIGURE 4.—Velocities measured in packing of glass spheres, compared with compression and shear velocities calculated by means of Equation (2).

displacement and a positive velocity intercept for the measured curve. The effect was not noticed by Iida, probably because the media acted more like "open" systems at the very low frequencies he used. Other assumptions that were made to simplify the theory will be investigated, in particular that of negligible friction between spheres and that of zero lateral constraint. Attention will be paid to the important conclusion of the theory that there exist three "phases" of propagation for each wave-normal, corresponding to three directions of vibration of the particles. This result, which is in agreement with the classical wave theory, has a particular significance in the models under discussion, namely that for horizontal propagation the compression wave (V_2) should have half the velocity of the vertically polarized shear wave (V_1) and that no horizontally polarized shear wave will be propagated. It is further hoped that studies may be extended to include packings of graded sands, and for this purpose a technique is being developed for measuring short time-intervals with a high-energy, non-repetitive source in the laboratory.

REFERENCES

Byerly, P. (1938). The earthquake of July 6, 1934: Amplitudes and first motion; Bull. Seis. Soc. Amer., vol. 28, no. 1, pp. 1–13.

Faust, L. Y. (1953). A velocity function including lithologic variation; Geophysics, vol. 17, no. 3, pp. 271–87.

Gassman, F. (1951). Elastic waves through a packing of spheres; Geophysics, vol. 16, no. 4, pp. 673–85.

Graton, L. C. and Fraser, H. J. (1935). Systematic packing of spheres with particular relation to porosity and permeability; Jour. Geol., vol. 43, pp. 785–909.

Hodgson, J. H. (1953). A seismic survey in the Canadian Shield; Pub. Dominion Observatory, Ottawa, vol. 16, no. 5, pp. 149–52.

Iida, K. (1939). Velocity of elastic waves in a granular substance; Bull. Earthquake Research Inst., Tokyo Imp. Univ., vol. 17, no. 4, pp. 783–807.

Jeffreys, H. (1929). The earth. 2nd ed., p. 184.

Krumbein, W. C. (1951). Some relations among sedimentation, stratigraphy and seismic exploration; Bull. Am. Assoc. Pet. Geol., vol. 35, no. 7, pp. 1505–22.

McCollum, B. and Snell, F. A. (1932). Asymmetry of sound velocity in stratified formations; Physics, vol. 2, pp. 174–85.

Stonely, R. (1949). The seismological implications of aeolotropy in continental structure; Royal Astron. Soc. Monthly Notices, Geophys. Supp., vol. 5, no. 8, pp. 343–53.

White, J. E. and Sengbush, R. L. (1953). Velocity measurements in near-surface formations; Geophysics, vol. 18, no. 1, pp. 54–69.

TRANSACTIONS OF THE ROYAL SOCIETY OF CANADA

VOLUME XLVIII : SERIES III : JUNE, 1954

SECTION FOUR

The Eocene-Oligocene Transition as a Time of Major Orogeny in Western North America

By LORIS S. RUSSELL, F.R.S.C.

Introduction

IN a previous paper in these transactions (Russell, 1952), a survey of the eastern ranges of the Rocky Mountains was made from New Mexico to British Columbia in an attempt to determine the times of orogeny along this portion of the Cordillera. These orogenies make up the so-called Laramide revolution, which is traditionally regarded as marking the close of the Cretaceous period. From the known ages of the pre-orogenic and post-orogenic sediments associated with these mountains it was shown that while there were late Cretaceous movements, and some in the Paleocene, the major diastrophism was of Eocene age, mostly in the early and late parts of that epoch.

The purpose of the present paper is to draw special attention to the orogenies that occurred in Late Eocene and earliest Oligocene time. Recently it has become evident that there are important rock and faunal sequences between what were formerly considered to be the uppermost Eocene and the lowest Oligocene sediments. Stimulus to prepare this summary was provided by field work on deposits of this age in southeastern British Columbia, and by an opportunity to examine the corresponding sediments in Utah and Wyoming. Within this part of the column are records of major diastrophism which is, in places, at least, the climax of the "Laramide" revolution.

Uinta Basin of Utah

This interesting area of sedimentary accumulation lies in northeastern Utah, between the Uinta Mountains on the north and the Colorado Plateaus on the south. A thick Palaeozoic and Mesozoic section terminates above with the Mesaverde formation, which is of Late but not latest Cretaceous age. It is overlain concordantly by several thousand feet of conglomerates and sandstones which are commonly referred to as the Wasatch, but which are more properly known as the Current Creek formation. This may be of Late Cretaceous age in its lower part, but probably also includes Paleocene and Lower Eocene portions (Walton, 1944, p. 119). Presence of these coarse clastics is taken to indicate an early stage in the uplift of the Uinta Mountains. It is unfortunate that a more precise dating of the Current Creek formation has not been possible as yet.

The overlying Green River formation represents a time of diastrophic quiescence and widespread lake deposition (Bradley, 1931). The characteristic sediments are finely laminated shales, oil-bearing in part. The lowest member, however, contains deltaic sandstones, some of which have yielded Middle Eocene mammals. This fossil occurrence confirms the general correlation of the Green River as the approximate equivalent of the mammal-bearing Bridger formation of Wyoming.

The quiet interval of Green River time was terminated by the spreading into the basin of fluviatile sands and clays, evidently the products of the erosion of rising mountains. The transition is a progressive one (Dane, 1954). These new sediments constitute the Uinta formation, the type mammal-bearing Upper Eocene of the Rocky Mountain region. The orientation of the channel sandstones and the petrology of the sediments themselves show that the source was at first mainly from the east, but as Uintan time progressed, the northern origin became more and more important (Stagner, 1942). This change is also reflected in the increase in reddish colour in the upper Uinta beds. Evidently a second episode of uplift in the Uinta Mountains began in Uintan time.

Overlying the Uinta is the Duchesne River formation, also mammal-bearing. Most students of the mammalian fossils regard the age of the Duchesne River as very late Eocene (Simpson, 1946), but when the components are separated into three groups corresponding to the three members of the formation, a good case can be made for drawing the Eocene-Oligocene boundary between the middle (Halfway) and upper (LaPoint) members. The Duchesne River sediments are more uniformly reddish than the Uinta, and contain coarser material, including conglomerates. They are predominantly of northern origin. The contact with the Uinta formation is transitional in the central part of the basin, but towards the northern margin the Duchesne River overlaps the Uinta and progressively older formations. The Duchesne River strata are only moderately tilted, whereas the Uinta beds have steep dips in places (Stagner, 1942, p. 283).

The sequence of events recorded by the Uinta and Duchesne River formations consists of progressive uplift along the north side of the basin, culminating at about the Uinta–Duchesne River transition in major mountain-building, followed by rapid erosion and deposition. In the broad sense the Uinta sediments are the flysche and the Duchesne River the molasse of the Late Eocene uplift of the Uinta Mountains. Most students of the region regard this as the most important episode in the development of this range. Some post-Eocene uplift is indicated by the moderate deformation of the Duchesne River beds and the deposition of the Bishop conglomerate (Bradley, 1936).

The Upper Eocene of the Uinta basin records a long time interval. Not only did it embrace the important physical events outlined above, but it also was the time of important faunal changes. Vertebrate palaeontologists

find four, or possibly five, distinctive mammalian faunas in the combined Uinta–Duchesne River sequence.

Wind River Basin of Wyoming

This is a large oval area in west-central Wyoming, lying between the Wind River Mountains on the south and the Owl Creek Range on the north. Over large parts of the basin the uppermost rocks are those of the Wind River formation (Lower Eocene), but along the margins both older and younger sediments are exposed. One of the most significant localities is the escarpment known as Beaver Divide, about twenty miles southeast of Lander. This has been studied in detail by Van Houten (1950), who has shown that there is an almost complete section of the Eocene here, beginning with the Wind River formation. This sequence terminates above in beds containing a well-defined Uintan or Upper Eocene mammalian fauna. The upper surface is irregular, channelled in places, and overlain by massive beds, with conglomerates (Beaver Divide member). The relationships of this unconformity to the mammalian faunas are still not completely clear, but it appears to mark the boundary between the Uintan and Duchesnean stages. Above the zone of Duchesnean mammals there are typical representatives of the Lower Oligocene (Chadronian) fauna. The diastrophic history of the Wind River Mountains as recorded on Beaver Divide is essentially the same as that of the Uinta Mountains: uplift in Late Paleocene or Early Eocene time, quiescence in the Middle Eocene, and a second uplift during the transition from the Uintan Late Eocene to the Duchesnean Late Eocene.

The Uintan and Duchesnean stages are also represented on the northeastern side of Wind River basin, along the southern margin of the Bighorn Mountains. The stratigraphy here has been well described by Tourtelot (1946). The principal sections of Upper Eocene rocks are along Badwater Creek, in township 39 north, ranges 88 and 89 west. The Uintan and Duchesnean rocks are similar lithologically, tuffaceous shales and marls, and although the actual contact of the beds with the Duchesnean fauna on those with the Uintan fauna has not been observed, it is probably conformable. The main deformation in this area was in Early Eocene time, as indicated by the conglomerates in the Wind River formation. However, there appears to have been much volcanic activity nearby in Late Eocene time. Subsequently the sediments underwent large-scale gravity faulting.

Flathead Valley of British Columbia

The valley of the North Fork of Flathead River lies in the extreme southeastern corner of British Columbia, and in adjacent Montana. This is the area of the Kishenehn formation, composed of non-marine sediments ranging from conglomerates to limestones. The structural relationships here were established by MacKenzie (1916). The Kishenehn strata rest dis-

cordantly on the Mesozoic formations, and are themselves folded and faulted. MacKenzie (1922) recognized that the age of the Kishenehn formation was a critical datum in the history of the Rocky Mountains. In my previous paper I offered a tentative dating as Middle Eocene. The more recent discovery of mammalian fossils in the Kishenehn has permitted a more precise age determination (Russell, 1954). The Kishenehn mammalian fauna is a mixture of very late Eocene and very early Oligocene forms. I am equating it with the fauna in the upper member of the Duchesne River formation of Utah, which is currently included in the Eocene, but which might well be regarded as earliest Oligocene.

It is clear that there were two episodes of deformation in the southern Canadian Rockies, one pre-Kishenehn, the other post-Kishenehn. The first not only folded and faulted the Mesozoic, but brought Beltian rocks to the surface, as shown by characteristic boulders in the Kishenehn conglomerates. The second movement was strong enough to produce dips of 30° or more in the Kishenehn strata.

It may be more than a coincidence that the Tertiary conglomerates of southwestern Saskatchewan, generally accepted as the erosion products of the newly uplifted Rocky Mountains, have two mammalian faunas, one of them of Uintan age, and the other early Chadronian. That is to say, they bracket in age the time of deposition of the Kishenehn formation. The hypothesis is here offered that the pre-Kishenehn uplift was of Uintan age, and from it gravels spread across the plains area, of which the Swift Current Creek beds are a remnant. Then came an interval of quiet during which the Kishenehn sediments were deposited. The post-Kishenehn uplift was of early Chadronian age, and from it was derived a second set of gravels, represented by the Cypress Hills formation. This implies, among other things, that the time interval from Uintan through Duchesnean to early Chadronian was a long and eventful one.

Other Areas

Reviewing the summary of times of orogeny given in a previous paper (Russell, 1952, p. 66), it may be noted that there are several other areas where the evidence is compatible with a Late Eocene dating of the principal uplift. In New Mexico the record in the San Juan basin indicates that the major movement of the Nacimiento Mountains was after Early Eocene and before Miocene time. The Front Range of Colorado is post-Paleocene and pre-Chadronian. At the southern end of the Absarokas, in western Wyoming, there is evidence of several stages of uplift, the last apparently being in Late Eocene time. Within the Bighorn Basin the final compression came after deposition of the Tatman formation, which is probably of Middle Eocene age. In the Black Hills region the oldest post-orogenic deposits are of early Chadronian age (Yoder and Lower Chadron). In western Montana there are deformed sediments of early Chad-

ronian age (Pipestone Springs beds) resting unconformably on the older rocks.

Summary

A number of distinct successive mammalian faunas are found in the Upper Eocene and basal Oligocene sediments of the eastern Rocky Mountain region, indicating that a long time interval is represented by these deposits. In at least three areas there is clear evidence of major diastrophism during this interval. There are several other areas in which such a dating of the orogeny is compatible with the available evidence. This conclusion is not intended to minimize the importance of the uplifts known to have occurred in Paleocene, Early Eocene, Miocene, and Pliocene time. It is suggested, however, that the significance of the disturbances during the Eocene-Oligocene transition has not been adequately appreciated.

REFERENCES

Bradley, W. H. (1931). Origin and microfossils of the oil shale of the Green River formation of Colorado and Utah; U.S. Geol. Surv., Prof. Paper 168, 58 pp., 3 figs., 28 pls.

——— (1936). Geomorphology of the north flank of the Uinta Mountains; U.S. Geol. Surv., Prof. Paper 185-I, pp. 163–99, pls. 34–45.

Dane, C. H. (1954). Stratigraphic and facies relationships of upper part of Green River formation and lower part of Uinta formation in Duchesne, Uintah, and Wasatch counties, Utah; Bull. Am. Assoc. Pet. Geol., vol. 38, pp. 405–25, 2 figs.

MacKenzie, J. D. (1916). Geology of a portion of the Flathead Coal area, British Columbia; Geol. Surv., Canada, Mem. 87, 53 pp., 1 fig., 2 maps.

——— (1932). The historical and structural geology of the southernmost Rocky Mountains of Canada; Trans. Royal Soc. Canada, Series III, vol. 16, Sec. IV, pp. 97–132, figs. 1–3.

Russell, L. S. (1952). Age of the front-range deformation in the North American Cordillera; Trans. Royal Soc. Canada, Series III, vol. 45, Sec. IV, pp. 47–69, figs. 1–9.

——— (1954). Mammalian fauna of the Kishenehn formation, southeastern British Columbia; Nat. Mus., Canada, Bull. 132, pp. 92–111, figs. 1–8, pls. 1–3.

Stagner, W. L. (1942). The paleogeography of the eastern part of the Uinta Basin during Uinta B (Eocene) time; Ann. Carnegie Mus., vol. 28, pp. 273–308, pls. 30–5.

Tourtelot, H. A. (1946). Tertiary stratigraphy in the northeastern part of the Wind River basin, Wyoming; U.S. Geol. Surv., Oil and Gas Invest., Prelim. Chart 22.

Van Houten, F. B. (1950). Geology of western part of Beaver Divide area, Fremont County, Wyoming; U.S. Geol. Surv., Oil and Gas Invest., Map OM 113.

Walton, P. T. (1944). Geology of the Cretaceous of the Uinta Basin, Utah; Bull. Geol. Soc. Amer., vol. 55, pp. 91–130, fig. 1, pls. 1–10.

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TRANSACTIONS OF THE ROYAL SOCIETY OF CANADA
VOLUME XLVIII : SERIES III : JUNE, 1954
SECTION FOUR

Variations in the Nickel Content of Some Canadian Trees

By HARRY V. WARREN, F.R.S.C., and ROBERT E. DELAVAULT

Introduction

IN 1940 K. Rankama reported a relationship between the content of nickel in vegetation and the amount of nickel present in underlying rock. Since then D. P. Malyuga (1947) and L. Reichen (1951) have carried out similar investigations in the Ural Mountains and the United States respectively. Nevertheless, the studies mentioned are of little value to a biogeochemist looking for nickel ore in Canada: not only are the plant species of the various areas different, but the above workers have provided no data concerning the response of different parts of plants to the presence of nickel mineralization.

Analytical Method

Experimentation has ended in the adoption, with minor modications, of the method described in the well-known book by E. B. Sandell (1951). The limit of sensitivity for one-gram samples of dry plant material lies close to 0.2 p.p.m. However, this sensitivity can only be obtained when no nickel-carrying precipitate is formed on the initial addition of ammonia. Such a precipitate may well sequester some nickel. The accuracy of the determinations on small samples, with low nickel content, cannot be guaranteed but fortunately a biogeochemist is primarily concerned only with richer samples.

Nickel Contents of Some Trees growing on Nickel Ore

In the Coast Range Mountains, about one hundred miles east of Vancouver, a disseminated nickel orebody has been developed by diamond drilling. However, the surface area has been little disturbed. Three species of trees are growing within two hundred feet of where mineralization is known. This mineralization may be more widespread, but only further work can determine this point. An exploration tunnel has been dug, but its level is well below the depth from which the samples were taken.

Twelve samples were taken and the resulting analyses were as follows:

A. Mountain Hemlock (*Tsuga mertensiana*)*
(Average from 8 samples)

Stems (Age by years)				*Mixed Needles*
1st year	2nd year	3rd year	4th & 5th year	
5(360)	5(320)	5(240)	5(250)	8(400)

*Analysis expressed in parts per million in dry plant followed by the parts per million, between brackets, in ash.

B. Mountain Fir (*Abies lasiocarpa*)*
(Average from 3 samples)

Stems Year				Needles Year			
1st	2nd	3rd	4th & 5th	1st	2nd	3rd	4th & 5th
15(870)	26(1230)	26(1260)	21(1000)	21(1090)	21(1300)	21(1240)	24(1030)

C. Western Red Cedar (*Thuga plicata*)

Green twig (3 years' growth)	Brown twig (4th & 5th year growth)	Older stems	Young tips	Mixed leaves
20(590)	8(250)	4(140)	36(1100)	32(840)

The pattern of distribution of nickel, at least in the younger organs for cedar, and in the whole bough for the other two, shows less tendency for preferential accumulation than is the case for copper, zinc, or molybdenum. Consequently any bulk sample of young growth may show a biogeochemical nickel anomaly.

Nickel Contents of Some Trees growing far from Mineralization

By way of comparison, some results are given from samples taken from areas remote from known nickel mineralization.

Mountain Hemlock (Tweedsmuir Park). Ten analyses were run of various samples of second- and third-year organs. Five contained less than .2 p.p.m. and the others ranged from .2(10) to .6(30) p.p.m. nickel.

Mountain Fir (Ymir). Sixteen samples collected from an unmineralized section averaged 1.4(50) in second-year needles.

Western Red Cedar (Vancouver Island). Six samples collected from above various rock formations averaged 1.5(50) in mixed leaves.

Possible Use of Nickel as a Pathfinder

The sixteen samples of Mountain Fir referred to above were part of a larger suite which included some samples taken in a nearby area on a rocky slope where an old tunnel had been driven to explore some scattered lead and zinc mineralization.

If samples taken over drift are considered negative and those from near the lead-zinc mineralization positive we can summarize our results as follows:

Nickel Contents in p.p.m.

A. Engelmann Spruce (*Picea Engelmanni*)	2nd year needles
(3 samples) positive	5(185)
(3 samples) negative	.8(30)
B. Mountain Balsam	2nd year needles
(2 samples) positive	4(145)
(16 samples) negative	1.4(50)
C. Western Red Cedar	Green twigs and leaves
(2 samples) positive	6(195)
(6 samples) negative	1.5(50)

Some of the trees which contained relatively high nickel had shown only a mild and not very convincing zinc anomaly. Nickel is not an important component of the mineralization in this area. Nevertheless, it is quite possible that nickel can be used in some areas as a pathfinder element for zinc in much the same way that molybdenum can be used for copper (Warren, Delavault, and Routley 1953).

It seems that some elements are capable of acting as pathfinders in vegetation just because they are present in much smaller amounts in nature and, consequently, provide a lower "background" content in vegetation. Small additions of such an element are much more conspicuous than small additions of an element which is much more abundant in vegetation.

Preliminary investigations by means of a spectroscope suggest that cadmium should also be investigated as a potential pathfinder element for zinc.

Some Eastern Canadian Results

Having in our collections some samples taken from above veins in the old Cobalt camp, others from the vicinity of an eastern township prospect containing nickel, and others from areas where no nickel is known to occur, we made a number of analyses with the following results:

Black and White Spruce (Picea mariana and Picea glauca). All twigs of spruce of two or three years of age from nickel-bearing areas ran 4(150) p.p.m. of nickel or better in contrast to those from negative areas which, without exception, carried less than 2(100) p.p.m. of nickel. Needles appear to carry approximately the same amount of nickel as the stems on which they grow. Where analysed, tips of boughs seem to be relatively low in nickel but of course the tips form a comparatively small portion of the bough.

Balsam (Abies balsamea). As far as nickel is concerned, balsam appears to behave much like the spruces, all positive samples running upwards of 4(100) and all negatives well under 2(100).

Deciduous trees. When our original collections were made, we had no intention of studying the biogeochemistry of nickel and for this reason we are not yet able to provide statistically useful data as to what is normal. However, on the basis of forty-eight analyses, the following generalizations may be useful as a basis for further work. (We must reiterate: None of our eastern Canadian samples came from nickel mines; our positives came from properties which are known to contain nickel, but only in modest amounts. Actually, we were surprised at getting measurable anomalies.)

Poplar (*Populus tremuloides*), White Birch (*Betula papyrifera*), Willow (*Salix sp.*), Pin Cherry (*Prunus pensylvanica*), Alder (*Alnus rugosa*), Maple (*Acer rubrum* and *Acer saccharum*) may all report abnormal amounts of nickel but possibly not as markedly as spruces and balsam. In general, all positive second- or third-year stems carry upwards of 2(40) p.p.m. of nickel and all negatives much less than this, the amounts usually being less than .3(10) and only occasionally rising to as much as 1(30).

Conclusions

On the evidence of more than two hundred nickel determinations, it seems clear that biogeochemical methods in some areas may prove useful in any search for buried nickel mineralization. Geochemical techniques generally may be particularly useful in sorting out geophysical anomalies caused by magnetite and/or pyrrhotite alone from those in which these minerals are accompanied by significant nickel mineralization.

Except for very young tips and stems more than four years old, the leaves and needles of most trees run from .2(10) to 2(100) p.p.m. over the more common geological formations. Over nickel mineralization, the nickel contents may rise from five to twenty times the above figures, with weak nickel occurrences providing intermediate results.

The ease with which even slightly abnormal amounts of nickel can be detected in some trees suggests that it may be considered a pathfinder element for base metal deposits such as zinc, much as molybdenum may, on occasion, be used for copper.

Acknowledgments

The Defence Research Board (Canada) and the Geological Survey of Canada have contributed a substantial portion of the funds which made this research possible. Western Nickel Limited, Kennco Explorations (Canada) Limited, New Jersey Zinc Limited, and B.C. International Engineering Company Limited, have all assisted materially by making possible the collecting of the necessary suites of specimens and by giving permission to publish some of the results which appear in this paper.

REFERENCES

Malyuga, D. P. (1947). On soils and plants as prospecting indicators for metals (in Russian); Izv. Akad. Nauk. S.S.S.R., Ser. Geol. no. 3, pp. 135–8.

Rankama, K. K. (1940). On the use of trace elements in some problems of practical geology; Soc. Geol. Finlande, Comptes rendus, vol. 14, pp. 92–106.

Reichen, Laura E. (1951). Geochemical field method for determination of nickel in plants; Anal. Chem., vol. 23, May, pp. 727–9.

Sandell, E. B. (1951). Colorimetric determination of traces of metals. New York: Interscience Publishers, Inc.

Warren, H. V., Delavault, R. E., and Routley, D. G. (1953). Preliminary studies of the biogeochemistry of molybdenum; Trans. Royal Soc. Canada, Series III, vol. 47, Sec. IV, pp. 71–5.

TRANSACTIONS OF THE ROYAL SOCIETY OF CANADA

VOLUME XLVIII : SERIES III : JUNE, 1954

SECTION FOUR

Some Glacial Features of Central Alberta

By P. S. WARREN, F.R.S.C.

Introduction

THE surface of most parts of the plains of Alberta is covered with a fairly thick mantle of glacial drift. The drift assumes various topographic expressions, varying from low ground moraine to the knob-and-kettle topography of terminal or recessional moraine. Pro-glacial laking has produced stratified deposits in some areas and wind-blown sand occurs locally. Special features, such as well-formed drumlins and esker ridges, are scarce. The original drainage pattern on the plains of Alberta has been markedly disrupted by repeated advances of the ice and the history of the main drainage channels of the present day is difficult to interpret from present data.

In spite of the great wealth of glacial material for study, little progress has been made in interpreting the history of the Pleistocene epoch in central Alberta. Considerable advance has been made in southern Alberta where the earlier geologists, undertaking reconnaissance work over wide areas, were attracted by various glacial features and attempted to classify and interpret the fine exposures presented to them. In central and northern Alberta, geological study has been confined mostly to the bedrock beneath the drift.

It is the intention of the writer to record various features of the glacial geology of central Alberta and to interpret them in so far as the data are sufficiently sound to make this possible. The writer wishes to acknowledge financial assistance from the University of Alberta Research Grant in carrying out the field work necessary for obtaining the results discussed in this paper.

Previous Work

In making his report on the geology of central Alberta, J. B. Tyrrell (1886) mentioned the glacial deposits of the area. He speaks of two till sheets separated by interglacial beds in the western part of the area, but failed to distinguish two tills in the eastern part. Glacial deposits, as observed in many places above the main drainage channels, lie on sands and quartzitic gravels which are usually termed "Saskatchewan gravels." Tyrrell gave these gravels a post-Tertiary age. This is much the same section of glacial drift as that occurring in southern Alberta which was first mentioned by G. M. Dawson (1884) and has been much discussed by geologists since

that time. D. A. Nichols (1931), working in the area northwest of Calgary, separated two belts of moraine which he considered to be of different ages. R. L. Rutherford (1937) studied the Saskatchewan gravels in central Alberta and considered them to be river deposits composed of materials from the west but not connected in any way with the Cordilleran glaciation as had been supposed by some earlier workers in southern Alberta. In 1937 Warren (1937) made an attempt to classify the morainal belts in central Alberta, especially for the purpose of showing the significance of the boundary between the morainal belts of eastern Alberta and the "Torlea flats" area with little or no moraine, lying directly west of them. He considered the morainal belts in western Alberta to be older than the moraines in eastern Alberta. Later Warren (1944) showed how glaciation affected the original drainage pattern of Alberta. In 1941 Rutherford (1941) drew attention to various glacial features in central and southern Alberta, especially to the boundary between the Cordilleran and Keewatin drifts. He considered that the moraines in eastern Alberta were younger than those nearer the foothills and postulated post-glacial uplift to account for some anomalies in the distribution of large erratics in southern Alberta. J. H. Bretz (1943) made a brief study of the moraines of Alberta which he mapped in part and from which he drew certain conclusions as to the age of the different belts. He considered that there was little difference in the age of the moraines in eastern and western Alberta. In 1945 R. F. Flint, chairman of the committee on the glacial map of North America, sponsored by the National Research Council of the United States (1945), published the results of previous work. This map includes the morainal belts of central Alberta so far as they have been mapped.

Till Sheets of Central Alberta

An examination of many Pleistocene exposures on the rivers and creeks, road cuts, and in strip mines and quarries in central Alberta has led to the conclusion that there are at least three tills in the area which may be differentiated by physical characteristics. A few exposures show the three tills in sequence so the age relationships are known. These complete sections as studied by the writer are mostly confined to exposures on the North Saskatchewan River in the immediate vicinity of Edmonton. The names in present use for the different tills are based on their physical characteristics and are as follows (in descending order): silt till, brown till, and grey till. The grey till is the oldest and may rest either on Saskatchewan gravels or on bedrock. It is not present in all exposures. The brown till has a wider distribution and appears to be the surface till over a broad area. The silt till is limited in its distribution and, where present, is always uppermost.

The till sheets are usually divided by waterlain deposits of sands and silts which we will term interglacial (interstadial?) beds. The interglacial beds between the grey and the brown tills are not always present, in which case

the brown till lies on the eroded surface of the grey till. The interglacial beds between the brown till and the silt till are usually silty in character, occasionally being sufficiently fine to be termed loess. Locally they become a fairly coarse sand. These beds are well known in the Edmonton area and have been studied in a few outcrops elsewhere.

An interesting feature with respect to all the till sheets is that they are comparatively thin as observed in most outcrops in areas of low topographic relief. The grey till is usually less than 10 feet thick, the brown till is thicker but seldom exceeds 20 feet. The silt till is usually less than 10 feet thick.

A table of the Pleistocene deposits, including the Saskatchewan gravels, is given below:

Pleistocene deposits of central Alberta

Silt till
    Strathcona sands and silts
Brown till
    Tofield sands and gravels
Grey till

Underlying strata, Saskatchewan gravels and sands, or
    Paskapoo or Cretaceous

Saskatchewan Gravels and Sands

A short discussion of the Saskatchewan gravels seems pertinent at this time as they are the underlying formation in many of our sections of glacial drift. The age of the beds is in doubt as no recognizable fossils have been obtained from them *in situ*. The formation has been thoroughly studied and discussed by R. L. Rutherford (1937). The source of the gravels is from the west as there are no Laurentian boulders contained in them. Quartzite, chert and arkose are the main pebbles. Limestone is rare. The writer agrees with Rutherford that there is no evidence in the area of central Alberta that the Saskatchewan gravels were associated with mountain glaciation. They are found in pre-glacial drainage systems laid down as river gravels, but may occur on fairly high benches. Their close association with the earliest till sheet gives the impression that they may be Pleistocene in age. The gravels are not consolidated and it is a point of interest that they were not entirely removed by erosion by the Keewatin glaciers. It is more probable that the Saskatchewan gravels were associated with the erosion of the Flaxville plain, following the uplift of the mountains and plains area in Pliocene? time (Warren, 1939). The age of Saskatchewan gravels, therefore, may be late Pliocene.

Grey Till

The earliest till sheet so far observed in central Alberta by the writer is here designated the grey till. It is always a grey colour, grading from a blue-grey to a brownish grey. This gradation of colour may be seen in a vertical section and the gradation also appears to have areal significance. In out-

crop the till appears to be a slightly sandy clay till with contained boulders from the Keewatin area. It is highly bentonitic. When wet it is extremely tough and sticky; when dry it is hard and brittle and tends to break up readily into sharp angular fragments. For this reason it produces a sloping cliff along river banks and may thus be identified even at a distance. The weathered surface is lighter in colour and may even assume a light-buff tint. There is no evidence of gumbotil in the bed. The finer analyses of this till have not been completed. Stringers of fine sand in the till were observed in one outcrop.

The grey till contains boulders from the Keewatin area but in most exposures they are not abundant. Quartzites, plutonics and gneisses are present in the order given. Weathering rinds have been observed on some of the quartzites, and a few well-decayed schistose rocks, which failed to stand up to handling, have been collected.

The thickness of the till varies greatly as the top always shows an eroded surface, whether overlain by interglacial beds or by the overlying till sheet. The grey till is generally absent in the higher topographic areas. In one exposure a bed of gravel composed of boulders from the Keewatin area marked the remnants of the grey till. The greatest thickness so far observed in outcrop is about 15 feet.

Tofield Sand

In some exposures where both the grey and the brown till are present, they are separated by a fine white quartzose sand which is here named the Tofield sand. The appearance of this sand is remarkably constant over wide areas and forms an excellent horizon marker. In two exposures the sand grades to a fine gravel near the top. The sand grains are well rounded when observed under binoculars and black minerals are fairly abundant. The thickness of the sand varies greatly, even in small outcrops. It seems to fill in channel depressions in the eroded surface of the grey till.

Fragments of shells have been collected from the sand, but none are identifiable. So far there is little evidence of any great amelioration of climatic conditions during the time the sand was deposited although peaty beds have been observed in one outcrop on the west side of Lake Manawan, near Edmonton.

The source of the Tofield sand is assumed to be the grey till beneath it. The name is derived from the town of Tofield, Alberta, where the formation is well exposed.

Brown Till

The brown till is younger than the grey till as many exposures show the brown overlying the grey till with or without intervening interglacial beds. It may be observed also resting directly on Saskatchewan gravels or on consolidated bedrock. The brown till grades from light to dark brown in colour and weathers to a buff colour. The thickest section observed is 15 feet and the till is fairly constant in thickness. The surface, where overlain by inter-

FIGURE 1.—Road cut about one mile south of Duffield, showing the silt till with a slice of brown till caught up in it. The slice of brown till is overturned to the south, showing the general direction of ice movement when the silt till was deposited.

FIGURE 2.—Exposure in wall of strip pit at Tofield, Alberta. Grey till is exposed at the base of the cut with strongly eroded and channelled surface. Interglacial sands *T* (Tofield), overlie the grey till *G*, filling the irregularities (showing smooth in the photograph), and overlain by the brown till *B* (top of section). Slump blocks of the brown till show on the exposed surface of the interglacial sands.

glacial beds, shows little erosion such as occurs on top of the grey till. In some low areas the lower half of the till shows rude stratification as if it had been deposited under water.

The matrix of the brown till is sandy and silty, thus differing in composition from that of the grey till. When wet, it is tough and sticky, and when dry it is hard and massive, and does not readily break down into fragments. Where no sign of stratification is present, the till stands as a vertical cliff and jointing tends to produce a columnar structure.

The brown till is stony with a wide assortment of boulders from the Keewatin area as well as local ironstone nodules, hard sandstone, and fragments of coal. Mica schists are not uncommon but they disintegrate easily and such fragments of limestone as have been found are so decayed that they may be crushed in the hand. Quartzites with weathering rinds are not common. As a rule the boulders in the brown till do not grade above medium size, but larger sized stones have been observed in the upper part.

The brown till is younger than the grey till but it is doubtful if the difference in age is great. The strong consolidation of the till is striking. No gumbotil has been observed.

Strathcona Sand and Silt

In low areas in central Alberta, such as in pre-glacial river valleys, the brown till is overlain by sands, silts and sometimes loess, here named the Strathcona sand and silt. These Strathcona beds in all areas so far observed were deposited in water, with the possible exception of some of the loess. These waterlain beds are overlain by the uppermost till—the silt till. It is probable that these interglacial beds were deposited in pro-glacial lakes which were dammed in low areas by the retreating glacier. Compressed masses of the brown till, apparently deposited in the pro-glacial lake by grounded blocks of ice, are observed in places in these sands and silts. When the deposit is silt, it is usually varved, especially where the deposit is thin. Thicker deposits of silt are apt to show a coarse banding with thick beds of silt and thin beds of clay. Where the main deposit is sand, it is apt to be topped by varved silts and clays. This tendency is well shown in the big sandpit in South Edmonton (Strathcona), from which locality the name is derived. When sand is present, the section of the lake beds is usually thick and the underlying brown till thins down to a few feet. Complete sections of the sand beds, together with the overlying and underlying beds, are difficult to obtain as slumping is produced by the unstable character of the sand.

The sands of the Strathcona beds differ greatly from those of the Tofield beds. The former are brownish in colour and contain much dark mineral, including coal. The silty fraction of the Strathcona beds is usually very fine and clean and commonly makes a perpendicular cliff along the river banks. It is apt to grade from very fine material in the lower beds to coarser above.

The thickness of the Strathcona beds varies greatly, ranging from 10 feet to 50 feet. The beds appear to have been deposited on quite an uneven surface which was probably due largely to original depositional irregularities

of the brown till. The character of the contact between the brown till and the Strathcona beds must be studied in more detail and over a wider area before definite statements can be made as to the length of the time interval, if any, between the two beds. They appear to be conformable.

The writer has studied the Strathcona beds on the banks of the North Saskatchewan River at Edmonton and along the Red Deer River, near the city of Red Deer. Both of these rivers occupy pre-glacial valleys in the areas studied. We have practically no knowledge of the Strathcona beds underlying higher areas.

Silt Till

The uppermost till sheet in central Alberta is here designated the silt till. The name is derived from the composition of the bed which is a silt of varying textures with only a few boulders. The origin of the bed is controversial. Recent evidence indicates that the uppermost bed exposed in west-central Alberta is the result of a distinct advance of the glacial ice. In low areas a rude stratification may be observed in the bed, but in higher areas this is lacking. Pro-glacial lakes were probably responsible for the incipient stratification. The bed is mostly remarkably free from boulders but commonly a few are present and in some exposures they are abundant. They are mostly rather small but stones up to two or three feet in diameter occur in places at the base of the till. All the stones are from Keewatin area.

The silt till as seen in the Saskatchewan River sections at Edmonton varies from 5 to 10 feet in thickness. It is never consolidated and has all the appearance of a very young till.

The silt till has been identified only in a limited area in Alberta. It extends a distance of some 35 miles west from Edmonton. The same bed overlies the lake silts on Red Deer River and tops the sand hills in the Wetaskiwin and Ponoka areas between Edmonton and Red Deer.

The glacier that deposited the silt till produced heavy ground moraine and also knob-and-kettle topography. Three drumlins in the vicinity of Edmonton were apparently formed by this glacier. The surface of these drumlins is stony. They strike in a north-south to a northeast-southwest direction. The reason for the lack of stones in the silt till in so many localities is not known.

The Moraines of Central Alberta

The strong morainal areas of central Alberta have been subject to more attention than the till sheets and attempts have been made to map them (Warren, 1937; Rutherford, 1941; Bretz, 1943). Between the heavily morainic areas, ground moraine is always in evidence in some form though it is sometimes so thin as to produce practically no topographic expression. One such area in eastern Alberta is termed the Torlea flats (Warren, 1937). Morainic material on this area is so thin that bedrock is commonly exposed

in shallow ditches and the expression of the morainic surface is little different from that of the lake beds which are present in the southern extension of the Torlea flats.

This flat area, in its entire extension from north of the North Saskatchewan River to the South Saskatchewan River and probably beyond, seems to divide Alberta into two distinct morainal areas which are very evident in crossing the province from east to west. The Torlea flats originally impressed the writer as a probable dividing line between older moraines on the west and the younger moraines on the east. The writer is now doubtful of such a division. The glacial history of Alberta does not lend itself to such an easy interpretation and until the significance of the Torlea flats is understood, it is preferable to withhold judgment as to the age of the morainal belts. A discussion of some characteristics of the main morainal areas, however, may be given at this time.

Coteau Moraine

The Coteau moraine extends in a northwest direction across Saskatchewan, entering Alberta at about the 53th parallel. It is usually considered the end moraine of a late Wisconsin glaciation. Where the Coteau moraine mixes with the heavy moraines of the Viking area, it is not easy to differentiate the two glaciations. The Viking moraines have a north-south trend in this area. In mapping the front of the Viking morainal area, Warren (1937) made no attempt to map end moraines as postulated by Bretz (1943). The north-south line drawn on Warren's map is the division between the Torlea flats and the area to the east which showed significant ground moraine or end moraine. North of the latitude of Edmonton, our present knowledge of the extension of the Coteau moraine is vague.

Viking Moraine

This is a series of moraines lying west of the Coteau moraine and east of the Torlea flats. The general trend of this moraine in central Alberta is north-south, but in southern Alberta it assumes a northwest-southeast direction. The writer has made no attempt to differentiate the various glacial features in this area. The moraines of the Viking morainal area in central Alberta have been mapped by Bretz (1943).

There is little doubt that the moraines of the Viking area were deposited prior to the advance of the glacier that deposited the Coteau moraine. The time interval between the two depositions, however, must remain a matter of doubt. Detailed stratigraphic work of the Pleistocene deposits over a critical area in eastern Alberta is at present being carried out by personnel of the Research Council of Alberta.

Buffalo Lake Moraine

Lying to the west of the Torlea flats, the Buffalo Lake moraine is a well-defined area, extending from north of the North Saskatchewan south to about latitude 52°. South of this the moraine splits and becomes confused

with the Drumheller pro-glacial lake area. The various ridges of moraine swing to a southeasterly direction in the Bow–South Saskatchewan River area. The northern portion of the Buffalo Lake morainal area is composed largely of moraines of the terminal type with a general north-south direction. It conforms to the pattern of the Viking morainal area to the east. In the Edmonton area the moraine is known locally as the Cooking Lake moraine.

The writer considers the Buffalo Lake moraine a recessional moraine. Good exposures of till in this morainic area about the latitude of Edmonton show that the surface till sheet is the brown till. Also the conformity in general trend and topographic expression of the Buffalo Lake moraine with the Viking moraine suggests that they are of about the same age and both of the recessional type.

Duffield Moraine

As considered in this paper, the Duffield moraine lies to the west of the city of Edmonton, extending from the Winterburn corner to near the town of Duffield, a distance of about twenty-five miles. This morainal area varies considerably in topographic expression. It includes areas of knob-and-kettle, well-developed ground moraine, and low swampy areas marking old drainage ways.

An examination of individual hillocks in road cuts shows the upper two or three feet to be fine sand or silt without stratification and with occasional boulders from the Keewatin area. The number of boulders is variable according to locality from total absence to plentiful. The central part of the hillocks are commonly composed of sands and silts which show some degree of fine stratification. Boulders are extremely rare. The stratification is commonly horizontal but may follow the contour of the hillock or be bevelled by the overlying non-stratified sands and silts. In some parts of the area wind action has in part shaped the hillocks and barchan types of dunes may be observed.

Various interpretations have been attempted to account for the Duffield morainic area. The writer has always been impressed by the morainal topography of the area, even though it has been modified in places by later wind action. The upper two to three feet of loose and unconsolidated beds on the hillocks is undoubtedly the silt till. The stratified silt and sand in the centre of the hillocks may be interglacial and later modified by the last glaciation. The action of the glacier on the underlying sandy beds is shown in an exposure about three-quarters of a mile north of Duffield where a slice of the underlying brown till has been caught up in a silt hillock and strongly bent over to the south (the direction of movement). There is little doubt that actual movement of the sand and silt in the centre of the swells was caused by the over-riding glacier, and this movement may have produced a shearing or false bedding in the overridden beds.

It is evident that the glacier that deposited the silt till and was responsible

for the Duffield moraine crossed the area from the north or northeast. This is shown by the strike of the drumlins in the vicinity of Edmonton and by the direction of elongated hills in the morainal area.

Another silt and sand area, similar in many ways to that at Duffield, occurs at Wetaskiwin, forty miles south of Edmonton. Topographically, the area is known as the Peace Hills and appears to be morainal in character, though much more affected by wind action than the Duffield moraine. Drumlin-like hills in this area have a north-south direction. A third sand and silt area with similar topography lies still farther south between Ponoka and Red Deer. Similar characteristics to those at Duffield and Wetaskiwin obtain here, but boulders appear to be much scarcer. These areas, however, cannot as yet be definitely linked with the Duffield moraine.

Sandy morainal areas are also present northeast of Edmonton but they have been studied only in reconnaissance.

The silt till is the youngest till in central Alberta and it appears to be quite restricted in area. The glacier that deposited it advanced from the northeast, passing to the west of the Cooking Lake hills. In eastern Alberta and western Saskatchewan the Coteau moraine probably represents the latest advance of the Wisconsin glacier. The front of the Coteau moraine strikes to the northwest and is believed to be present about forty to fifty miles northeast of Edmonton. The writer puts forward the hypothesis that a lobe from this glacier may have advanced to the southwest through the low land along the North Saskatchewan River between the Cooking Lake hills, southeast of Edmonton, and an upland locally known as the Glory Hills, northwest of Edmonton. It may have extended as far south as Red Deer River. This hypothesis would explain the sandy character of the till because the lobe advanced only over low, flat land where sandy lake beds were present (and are still partially preserved). These provided a local source of sediment for the silt till. This hypothesis would account for the lack of boulders in the till in so many localities.

Age and Correlation of the Central Alberta Tills

Two tills from the Keewatin area are exposed in many places in southern Alberta and these tills are separated in places by interglacial (interstadial?) beds. The lower till is grey and the upper till a buff or brown colour. These two tills are probably the same as the grey and brown till of the Edmonton area although proof is still lacking. The writer is satisfied that he has identified the grey and brown tills of the Edmonton area as far south as Red Deer River, but cannot trace them through to the exposures on Oldman River in southern Alberta. A third or silt till has not been identified with any certainty farther south than Red Deer River. It is undoubtedly premature to attempt a correlation of the Alberta tills with those exposed on Swift Creek in Saskatchewan (Wickenden, 1930).

The age of the three tills of Alberta in the terms of glacial stages as defined in the Upper Mississippi valley area is not known. It will probably be

a difficult matter to make any exact correlation with that area, based on the amount of weathering or leaching that has taken place since the tills were deposited. Alberta lies largely within the rain shadow of the Rocky Mountains and the climatic conditions in interglacial times were probably similar to those of the present day. A till or moraine in Alberta would have the appearance of being "younger" than one of a similar age in an area of higher temperatures and heavier rainfall. The grey till in central Alberta has the appearance of an old till judged by the character of rocks preserved in it and the amount of induration. The overlying brown till contains some friable rocks such as mica schist and limestone which are usually capable of being crushed by the hand. It also weathers to a very solid rock under pressure of overlying lake beds or later till. The silt till has the appearance of a young till. It is completely unconsolidated but this may be due to the lack of sufficient binding material for the high percentage of sand and silt of which it is composed. Until more accurate age determinations are available the correlation of the Alberta tills with the Mississippi valley Pleistocene beds should not be attempted.

REFERENCES

Alden, W. C. (1932). Physiography and glacial geology of eastern Montana and adjacent areas; U.S. Geol. Surv., Prof. Pap. 174.

Alden, W. C. (1924). Physiographic development of the northern Great Plains; Bull. Geol. Soc. Amer., vol. 35, pp. 385–423.

Alden, W. C. and Stebinger, E. (1913). Pre-Wisconsin glacial drift in the region of Glacier National Park; Bull. Geol. Soc. Amer., vol. 24, pp. 529–72.

Allan, J. A. (1943). The relation of the geology to the soils in the Rosebud and Banff sheets; App. to Soil Survey of Rosebud and Banff Sheets, Univ. of Alberta, College of Agriculture, Bull. no. 40, p. 123.

Bretz, J. H. (1943). Keewatin end moraines in Alberta, Canada; Bull. Geol. Soc. Amer., vol. 54, pp. 31–52.

Coleman, A. P. (1909). The drift of Alberta and the relations of the Cordilleran and Keewatin ice sheets; Trans. Royal Soc. Canada, Series III, vol. 3, Sec. IV, pp. 3–12.

Dawson, G. M. (1884). Report on the region in the vicinity of the Bow and Belly Rivers; Geol. Surv., Canada, Report of Progress, pp. 139c–152c.

Dawson, G. M. with McConnell, R. G. (1895). Glacial deposits of southwestern Alberta in the vicinity of the Rocky Mountains; Bull. Geol. Soc. Amer., vol. 7, pp. 39–41.

Flint, R. F., Chairman (1945). Glacial Map of North America, pts. 1 and 2; Geol. Soc. Amer., Sp. Pap. no. 60.

Johnston, W. A. (1933). Quaternary geology of North America in relation to the migration of man; *in* D. Jenness, The American aborigines, pp. 9–45. University of Toronto Press.

Johnston, W. A. and Wickenden, R. T. D. (1931). Moraines and glacial lakes in southern Saskatchewan and southern Alberta, Canada; Trans. Royal Soc. Canada, Series III, vol. 25, Sec. IV, pp. 29–44.

Nichols, D. A. (1931). Terminal moraines of the Pleistocene ice sheets in the Jumpingpound–Wildcat Hills area, Alberta, Canada; Trans. Royal Soc. Canada, Series III, vol. 25, Sec. IV, pp. 49–59.

Rutherford, R. L. (1937). Saskatchewan gravels and sands in central Alberta; Trans. Royal Soc. Canada, Series III, vol. 31, Sec. IV, pp. 81–95.

——— (1941). Some aspects of glaciation in central and southwestern Alberta; Trans. Royal Soc. Canada, Series III, vol. 35, Sec. IV, pp. 115–124.

Slater, G. (1927). Structure of the Mud Buttes and Tit Hills in Alberta; Bull. Geol. Soc. Amer., vol. 38, no. 4, p. 721–30.

Tyrrell, J. B. (1886). Report on a part of northern Alberta and portions of adjacent districts of Assiniboia and Saskatchewan, embracing the country lying south of the North Saskatchewan River and north of Lat. 51°6′ and between Long. 110° and 115°15′ west; Geol. Surv., Canada, Ann. Rept., pt. E.

Warren, P. S. (1937). The significance of the Viking moraine; Trans. Royal Can. Inst., vol. 21, pt. 2, pp. 301–5.

——— (1939). The Flaxville plain in Alberta; Trans. Royal Can. Inst., vol. 22, pt. 2, no. 46, pp. 341–9.

——— (1944). The drainage pattern of Alberta; Trans. Royal Can. Inst., vol. 25, pt. 1, pp. 3–14.

Wickenden, R. T. D. (1930). Interglacial deposits in southern Saskatchewan; Geol. Surv., Canada, Sum. Rept., pt. B. pp. 65–71.

Williams, M. Y. (1929). The physiography of the southwestern plains of Canada; Trans. Royal Soc. Canada, Series III, vol. 23, Sec. IV, pp. 61–79.

TRANSACTIONS OF THE ROYAL SOCIETY OF CANADA
VOLUME XLVIII : SERIES III : JUNE, 1954
SECTION FOUR

The Changing Worlds of Geology and Geophysics

By J. T. WILSON, F.R.S.C.

The hills are shadows and they flow
From form to form, and nothing stands;
They melt like mist, the solid lands,
Like clouds they shape themselves and go.

IN these words Tennyson epitomized the geological principle that nothing on the earth's surface is constant but change. The same thought might be applied with equal truth to the science of geology itself, for in Tennyson's time it was very different in content and in its relation to other branches of science from geology today. Although it was of less practical value then than now, it was relatively better known to the public. Physics and chemistry had not risen to their present prominence, for their modern techniques were unknown, but geological surveys were already well established. Indeed the first scientific investigations attempted by the governments of most countries were geological. From that early work stemmed debates about the date of creation, the reality of the flood, and the possibility of evolution, which aroused public attention and controversy as great as that now centred about atomic energy. The founders of the Royal Society of Canada included numerous geologists, from whom the first president was chosen.

The content of geology has changed, too, though not as radically as that of other sciences. In the seventh edition of the standard textbook of a century ago, Lyell's *Principles of Geology* (1847), mention of many familiar topics such as faulting and the Precambrian is largely missing. Also discussion of the origin of the earth is barred as it would have been blasphemous; but nevertheless there is included a much broader study of the earth than is included in geology today. Seventeen chapters, exactly one-third of the book, are devoted to the subjects of earthquakes, volcanoes, ocean currents, climatology, changes in level of land and sea, and other matters still mentioned by geologists but in fact studied by several different groups of geophysicists. Lyell was not merely an interested commentator upon these subjects. He was the great authority.

As Hubbert has strongly pointed out geology has greatly diminished in scope whereas the branches it has shed have been picked up by others and developed into independent fields of study. As early as 1901 the *Oxford English Dictionary* marked as obsolete the definition of geology as the science which treats of the earth in general and gave a definition restricting

it to certain kinds of investigations of the earth's crust. This curtailment has, of course, been a consequence of the increase in our knowledge and the impossibility of imparting the whole mass of information to students. Faced with this dilemma geologists retained those aspects of the subject of greatest concern to field geology or geological mapping, which until recently was their chief occupation. The various branches of geophysics were left to develop largely in the hands of physicists with little knowledge of or concern with geology.

This growth of a series of splinter groups of earth sciences (for surely the earth's interior, its earthquakes, its oceans, and its magnetic field are as much a part of it as its rocks) passed almost unnoticed until certain recent and drastic changes occurred in our knowledge of the earth. These changes began about twenty-five years ago but their full impact has only been felt within the last eight. They have already led in turn to great advances in methods of prospecting and they are causing many astronomers and physicists to take an interest in the earth which they did not take before. The trend toward ever narrower specialization in geology and geophysics has been reversed and some of these fields are being reunited. The fact is that methods available for studying the earth have changed radically in the past few years and that this is a time when we geologists should reconsider what we are trying to do and how best we can do it with the new tools which are available for us.

As an example, consider the situation in the petroleum industry in western Canada. It is well known that there are few outcrops on the prairies and only a small proportion of oil geologists are engaged in field mapping. Many are examining drill cores and subjecting them to measurements in laboratories. All drill holes are now logged by physical devices and not less than $40,000,000 annually is being spent upon 150 seismic exploration crews. The key men in prospecting for oil are not field geologists making maps, but men who spend most of their time in offices and in laboratories integrating physical graphs and records with laboratory studies of drill cores and with geological cross-sections and maps in an endeavour to interpret complex patterns in three dimensions. It is not that the need for an understanding of geology has been displaced by physical measurements; if anything, more geological insight is needed to make three-dimensional studies than is required to make two-dimensional maps. Men are needed who can understand and deal adequately with both physical and geological aspects of the work.

A similar change has happened in mining prospecting, but to a smaller degree. It is true that important deposits like those of Labrador and Manitowadge are still being found by traditional methods, by hard work and by good luck in following up the records of old field expeditions, but others like Marmora and Bathurst have been wholly or partly discovered and developed by physical methods of prospecting. The government departments have recognized the change. For example, according to its annual

report the Department of Mines and Technical Surveys in 1952 issued 35 aeromagnetic maps compared with 40 geological maps and reports. Provincial Surveys are doing the same thing and the Dominion Observatory has already issued gravity maps of six provinces.

That these remarkable changes have occurred in prospecting is common knowledge, but the fact that similar methods have had as great an effect upon our knowledge of the earth as a whole is less widely appreciated. For a long time geologists have had considerable knowledge about the land surface exposed over a quarter of the face of the earth. Geomagneticians and seismologists have acquired through the years much information on their subjects but extensive gravity data and a knowledge of the nature of the ocean floors have been gained only within the last few years. The number and thickness of layers in the core, mantle, and crust have gradually been defined but the amount of radioactivity and the temperatures at different depths in these layers have been very difficult to ascertain. Within the last two years several independent estimates of internal temperatures have been made. These are in good agreement. The problem of distribution of radioactive elements can be tackled by analogy with meteorites and because rather close limits can be placed on it by thermal considerations.

All these new data suggest a very exciting possibility. It is that we may be able at last to discover how the earth operates. The earth is undoubtedly a heat engine, by which we mean that it has sources of heat, it does work, and it radiates heat. It is indeed a very powerful engine, of the order of ten billion horsepower according to data given by Gutenberg and Richter. Much of its energy is released in earthquakes. These are powerful, for not only do they devastate thousands of square miles every year but major earthquakes regularly shake the whole earth and are recorded by seismographs everywhere. Major earthquakes are an evidence of mountain building in progress, and if we could find out how the earth operates we would discover the major cause of geological changes. The hope that we should be able to do this, and do it soon, does not seem at all unreasonable, when we consider that the earth is in reality an ordinary sort of machine.

Below us at a depth of 2900 kilometres is the white-hot, molten iron of the earth's core. This distance is about as great and is about as accurately known as is the distance of the more remote Arctic islands from southern Canada. There is good reason to believe that the temperature of the core is that of a hot furnace and that pressures there are about ten times greater than those already attained in laboratories. It is the effect of the hot and active interior that builds mountains, shapes continents, and thus allows erosion to take place.

The behaviour of molecules and atoms which are too small for us to comprehend has been reduced to useful and precise theory. The nature of the stars and galaxies, which are farther away and more inaccessible to us than we can properly visualize is nevertheless being propounded in logical ways. If there are laws that govern the behaviour of such extreme objects

(and many of these laws have only been discovered this century), then surely the earth with its moderate dimensions also operates according to precise rules and it is not too much to suggest that we may be able to discover them. If we can predict in advance how to operate an atomic pile, surely we can also discover, with equal precision, how a mountain range is built. When we consider how commonplace is the nature of the earth compared with the mechanisms of atoms and galaxies, it is reasonable to suppose that we can discover how it operates. The great lacunae in our knowledge of the earth which prevent us from solving this problem are now largely in process of being filled. The most formidable which remains is the problem of geological time. Geological processes operate so extremely slowly that we cannot hope to observe them adequately during our own lifetime. In particular we need to know the record during early Precambrian time when the radioactive elements had not decayed so much and were more abundant and the earth was possibly more active. This problem of the proper understanding of Precambrian time (which constitutes at least four-fifths of all recorded geological time) is a particularly suitable one to study in the Canadian Shield.

The advantages to be obtained from the solution of this problem are obvious enough. On the one hand geology and the various branches of physics of the earth would all be united by a common theory and on the other hand we would have a framework upon which to arrange the multitudinous observations of field geology in an orderly fashion—for it is too much to suppose that any theory of the earth would be more than a general guide and even a good theory could not explain the details found in large-scale mapping. We can also say that in other sciences great advances in theory have always brought great economic advantages with them, but it is too early to define yet what these would be in the case of the earth.

The problems facing students of the earth are therefore clear. They must both adjust themselves to additional methods of prospecting and endeavour to find out the method of operation of the earth. The first problem is one in applied science, the second is one of the most outstanding in pure science today.

In all other branches of science there is a clear-cut distinction between the pure and applied aspects, between chemists and chemical engineers, between botanists and agriculturalists, between physicists and electrical and mechanical engineers, between pathologists and practising doctors. Such a distinction should be more clearly made in geology and geophysics. At present we have one group trained to do field geology and one trained to do field physics. What we want is one group looking for minerals and petroleum by all methods, geological, chemical, and physical, and another smaller group trying to advance our knowledge of the earth.

Besides making sharper this distinction between pure and applied geology we need to adjust and prune our courses so that physicists studying the earth will learn some geology and some geologists will learn more physics.

In so varied a subject as the earth there will long remain room for plenty of specialists from palaeontologists to designers of airborne magnetometers, but we need a larger proportion of men who can bridge the gap which has too long existed between physics and geology.

The wealth of activity now evident in Canada in all these fields, the interest of companies, governments, and universities alike in pursuing these studies, and the natural advantages provided by the varied geology and great size of our country give us much reason to hope that we can contribute both to the improvement of prospecting and to the solution of the most fundamental and fascinating of all problems in terrestrial science.

Sciences progress through pauses and through spurts of creative energy. It would appear that the earth sciences have started to make an abrupt climb after a sojourn on a long plateau. There is a tense expectancy as new discoveries are awaited. It is an exciting time to be studying these sciences for we can perhaps expect to see in our lifetime great advances in our understanding of the earth.

> O earth, what changes hast thou seen!
> There where the long street roars, hath been
> The stillness of the central sea.

PRINTED IN CANADA
AT THE UNIVERSITY OF TORONTO PRESS